SOURCE OF DETRITAL HEAVY MINERALS IN ESTUARIES OF THE ATLANTIC COASTAL PLAIN

A THESIS

Presented to

The Faculty of the Division of Graduate

Studies and Research

by

James Neiheisel

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

in the School of Geophysical Sciences

Georgia Institute of Technology

April, 1973

ACKNOWLEDGMENTS

The author acknowledges the assistance and guidance received from Drs. Charles E. Weaver, Herbert L. Windom, and Kevin Beck of the Geophysical Science Department of the Georgia Institute of Technology. Fieldwork was done chiefly from U. S. Army Corps of Engineers, Philadelphia District vessels and laboratory analyses at the U. S. Army Corps of Engineers, South Atlantic Division Laboratory. Special laboratory testing was performed at the Geophysical Science Department at Georgia Tech and the Geology Department at Georgia State University.

Appreciation is extended to Dr. David B. Duane of the Coastal Engineering Research Center for 24 sediment samples from the CERC sand inventory program of the New Jersey continental shelf area. Special thanks is also extended to Dr. R. R. Jordan of the Geology Department of the University of Delaware for three beach samples from Rehoboth Beach, Delaware.

Philadelphia District, Corps of Engineers provided ship-time, personnel, and equipment for obtaining the 140 bottom samples in the Delaware estuary. Special thanks is extended to Mr. Paul Hartzel and Mr. Bruce Uibel for their aid in procuring the field samples.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Concluded)

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Concluded)

SUMMARY

Estuaries of the Atlantic Coastal Plain contain a northern group characterized by embayments, large size, and associated with Pleistocene glacial deposits and a southern group smaller in size and considerably removed from primary source rocks. Sediments within these estuaries contain heavy-mineral suites which reflect their source as fluvial Piedmont, fluvial Coastal Plain, Continental Shelf, or mixtures of these three possible sources. Heavy mineral patterns of the well mapped Continental Shelf sediments set the tone for differences that might be expected in the more poorly explored northern estuaries of the Atlantic Coastal Plain.

Analysis of the heavy minerals from bottom sediments of the large embayed Delaware estuary in the northern Atlantic Coastal Plain reveals four heavy-mineral provinces from the head of tide at Trenton to the Continental Shelf area in the vicinity of the capes. From Trenton to the bay, a fluvial Piedmont source is characterized by a "full" heavy-mineral suite rich in hornblende and garnet; measured tonnages of heavy minerals from the Piedmont and Coastal Plain streams discharging into the river estuary, which is ideally situated parallel to the Fall Line between these contrasting physiographic provinces, reveals that approximately five times the amount of transparent heavy minerals are contributed annually from Piedmont streams as compared to the amount from Coastal Plain streams. The progressive change of the heavy minerals from head of tide to the bay

is reflected in heavy mineral dispersal patterns. The major portion of Delaware Bay contains a heavy-mineral province of mixed fluvial Piedmont and fluvial Coastal Plain source materials characterized by a sillimanite-rich, "full" heavy-mineral suite. Toward the lower eastern and central portions of the bay there exists a mixed glacially-derived, Continental Shelf heavy-mineral suite and "Delaware Bay" heavy-mineral suite with a dispersal pattern of increasing sillimanite into the bay along the eastern side of the lower bay; this province is characterized by four to eight percent sillimanite. The coastal area and Continental Shelf off the New Jersey coast contain a heavy-mineral suite characterized by an impoverished sillimanite fraction; the Delaware coast by contrast contains a heavy-mineral suite similar to Delaware Bay.

The hydrodynamics in the vicinity of the capes is reflected in sillimanite dispersal patterns. Sediment drift, littoral currents, and sillimanite dispersal show that sediment from the New Jersey coast is partly deposited on the shoals off Cape May and another increment is transported landward into the eastern portion of the bay around Cape May for dispersal into the lower eastern and lower central portions of the bay. Delaware Bay sediment, characterized by a sillimanite-rich heavy-mineral suite is transported seaward along the western portion of the bay along the Delaware submarine channel in a southeasterly direction; this feature represents ancestoral Delaware estuary 7,000 years ago. Delaware coastal sands, with a heavy-mineral suite rich in sillimanite, are transported by northerly littoral currents into the bay and are actively extending Cape Henlopen into the western portion of the bay area.

Thus, heavy-mineral dispersal patterns reflect a net seaward transport of sand-size sediment from the Delaware River into the embayed portion of the estuary where the sediment mixes with eroding bay beaches. Some sediment appears to be transported seaward via the Delaware submarine channel along Pleistocene carved surfaces. Landward transport of sand-size sediment occurs around both capes into the bay, but the sediment does not mix across the capes.

The heavy minerals of the southeastern estuaries differ in the main from those of the northern Atlantic Coastal Plain estuaries in the absence of glacially derived sediments and a Piedmont source heavy-mineral suite rich in epidote and hornblende but meager in garnet. Coastal Plain sediments, older than Pleistocene in age, are similar to those of the northern Atlantic Coastal Plain in being impoverished in unstable mineral species. The predominant fluvial Piedmont source of heavy minerals in Santee, Savannah, and Altamaha River estuaries is readily recognized by the high ratios of epidote and hornblende in the heavy-mineral assemblage. The heavy minerals of Charleston, Brunswick, Broad, and Satilla estuaries, situated at the mouths of streams confined to Coastal Plain sediments, do not reflect their sediment source as the watershed but instead reflect a source from the Continental Shelf in the presence of epidote and hornblende of similar ratio as adjacent Continental Shelf sands. The southeastern Continental Shelf heavy-mineral assemblage appears to be largely a fluvial Piedmont source with heavy-mineral dispersal patterns from eroding fluvial land forms deposited during the Pleistocene when sea level was lower; on a transgressing sea the large fluvial Piedmont deposits are the main sediment source to be eroded and fed to the littoral currents for transport.

Charleston estuary reflects the imbalance on the sediment regimen in an estuary resulting from the recent intervention by man's diversion of a large Piedmont source stream, Santee River, into a small Coastal Plain estuary in order to gain hydroelectric power. The Charleston harbor sediments reflect the fact that sand-size sediments are effectively stopped by the man-made reservoir but clay minerals from the Piedmont source are transported and trapped in the estuary contained in Coastal Plain formations; sediment transport of some sand-size sediment into the harbor from the Continental Shelf source area is reflected in hornblende dispersal patterns. Thus, clay from the watershed is flocculated and trapped to form 95 percent of active sedimentation in the estuary while sand-size sediment from the high energy coastal area impoverished in clay is contributing sand from the Continental Shelf to form the other five percent of sediment trapped in Charleston harbor.

CHAPTER I

INTRODUCTION

Purpose and Scope

The estuaries of the Atlantic Coastal Plain are situated in the tidal regions of stream mouths at the interface between the fluvial and marine environments. These features range in length from several miles in the smaller southeastern estuaries to greater than a hundred miles in the larger northern estuaries of the Atlantic Coastal Plain (see Figure 1). The hydrodynamics affecting sediment distribution within the estuaries is complex since unidirectional but extremely variable fresh water discharge occurs from the watershed on the landward side while tidal currents carry variable volumes of marine waters in and out the estuary on a reversing diurnal tidal cycle. Sediments transported and deposited in the estuary are related to their availability in these contrasting terrigenous and marine source areas and in the hydraulic regimen of the estuary.

Analysis of heavy minerals in the sand-size sediments of the estuaries provides a means of reflecting source areas, and by dispersal patterns of diagnostic minerals, to delineate net transport sediment directions. The probable source areas possible to delineate by heavy minerals fall into three categories which are (1) Piedmont Formations, (2) Coastal Plain Formations, and (3) the Continental Shelf.

While heavy mineral provinces have been delineated on the Atlantic

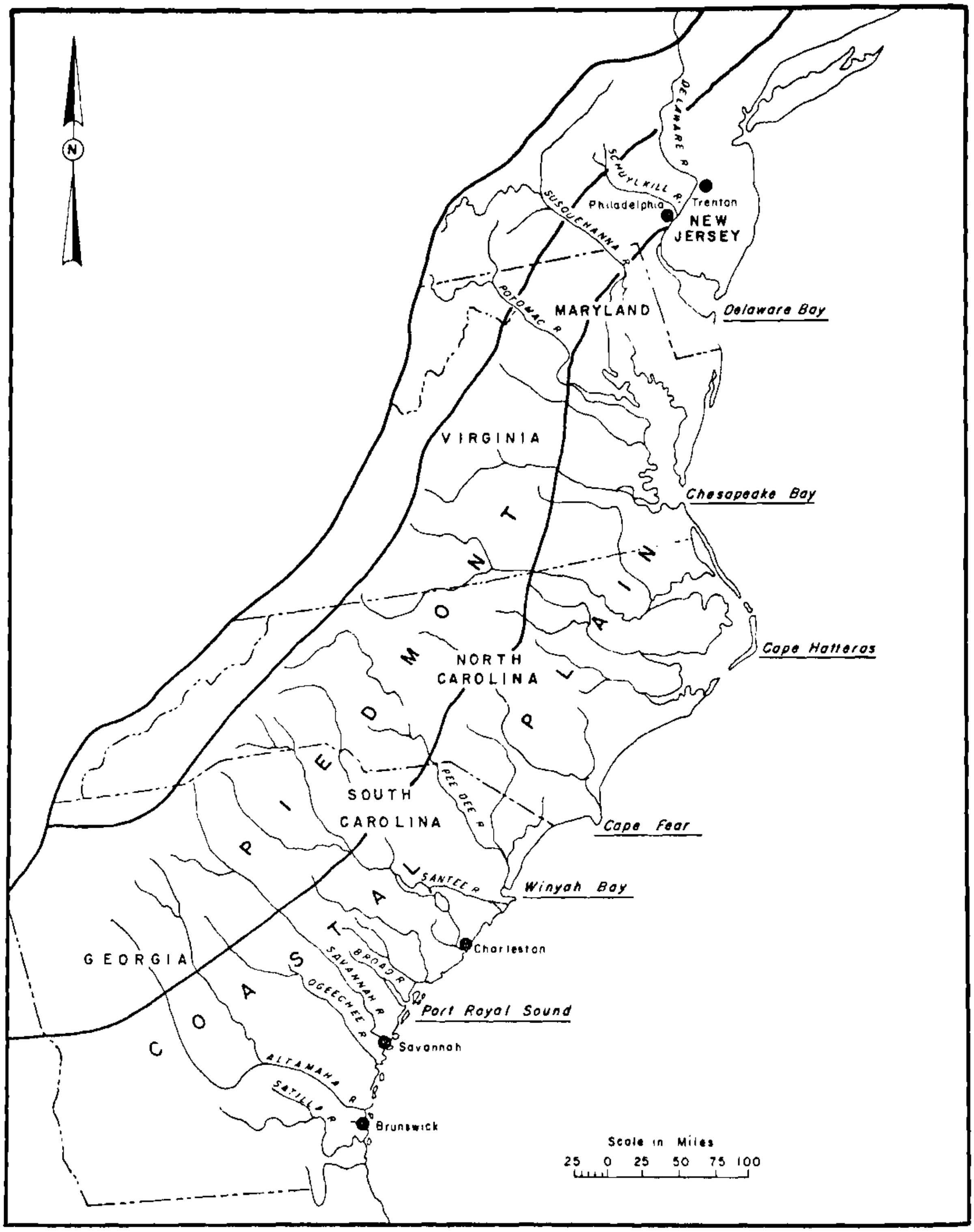


Figure 1. Location of Principal Rivers and Estuaries of the Atlantic Coastal Plain

Continental Shelf by extensive investigations by Milliman et al. (1972), Ross (1970), Pilkey (1962), and others, the Atlantic Coastal Plain estuaries have been only sparesly investigated for their heavy mineral content. The heavy minerals of the rivers and estuaries of the smaller southeastern estuaries have been reported in fair detail by Hails and Hoyt (1972), Windom, et al. (1971), Neiheisel and Weaver (1967), and others; however, heavy mineral analysis of the larger northern Atlantic Coastal Plain estuaries to date have been merely of a reconnaissance nature. Biggs (1965) has reported on several locations in Chesapeake estuary and Strom (1972), Moxley (1970), Jordan and Groot (1962), and McMaster (1956) have conducted limited investigations in portions of the Delaware estuary. The purpose of this investigation is to systematically evaluate the source of detrital heavy minerals from one of the large embayed estuaries of the northern Atlantic Coastal Plain and to correlate the findings with the heavy mineral provinces of the Continental Shelf. Comparison will then be made with the investigations of the other estuaries of the Atlantic Coastal Plain.

The Delaware estuary was selected for the investigation because it is ideally located between two major physiographic provinces, the Piedmont and Coastal Plain. From the head of tide at Trenton to the embayed portion of the estuary, the bay area is relatively uncomplicated in shape with simple shoreline development. The Delaware estuary has also been studied by various state and federal agencies so that considerable data are available in knowledge of sediment load and hydrodynamic factors. (See Figure 2.)

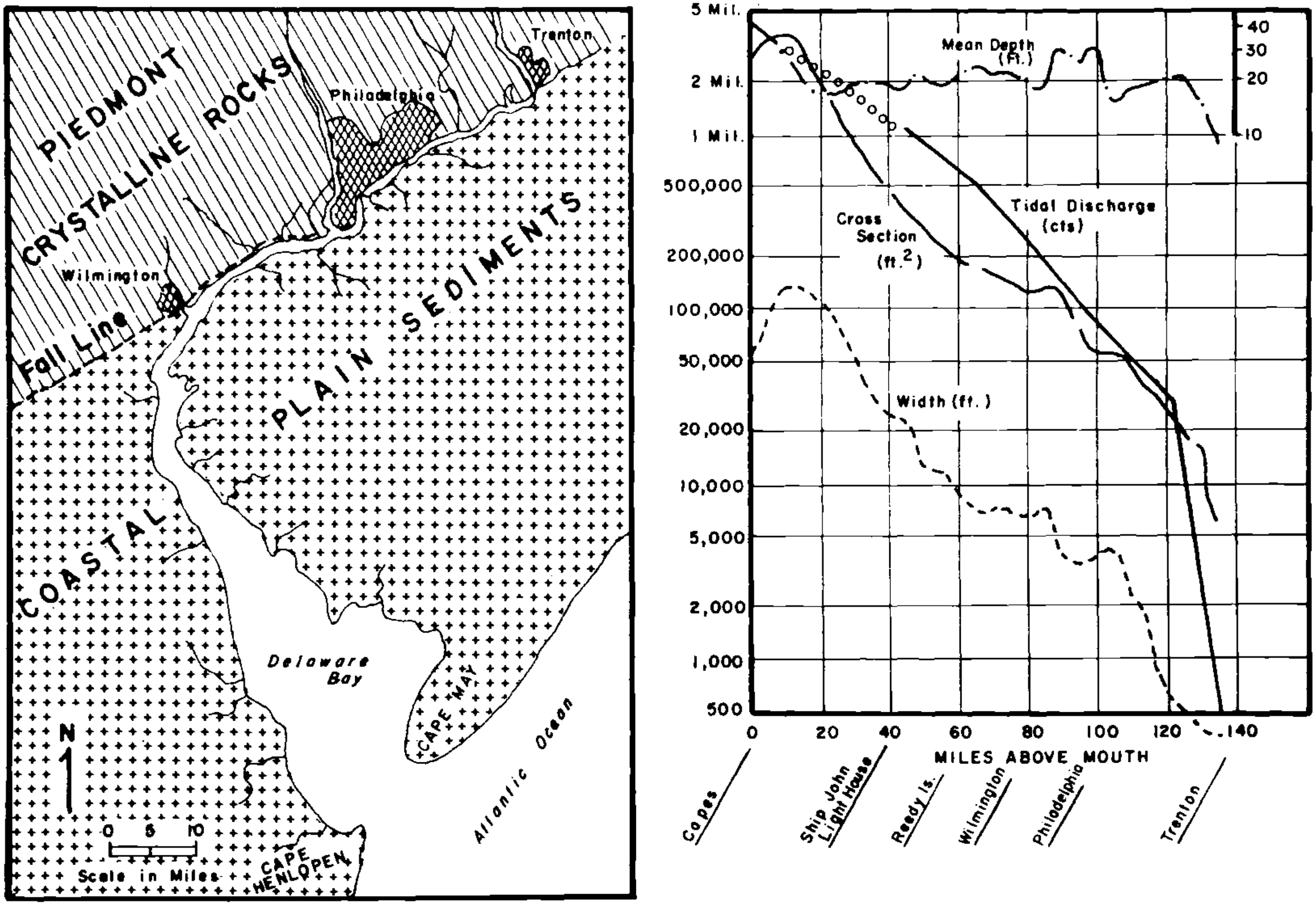


Figure 2. Index Map and Physical Characteristics of Delaware Estuary

Nomenclature

The terminology applied to various features and parts of the study area follows the Glossary of Geology (A.G.I., 1972). A term of wide usage but varying in definition is the term estuary which may be classified from several points of view. The Atlantic Coastal Plain estuaries might be defined by a geomorphologist as a "drowned river-mouth" while an oceanographer's classification would include the concept of the farthest point inland where seawater is measurably diluted with fresh water. The classification by Ippen (1966) and others who stress tidal dynamics in estuaries will be employed in this investigation; this classification extends the estuary to the "head of tide." The Delaware estuary is by definition that portion of the Delaware watershed from the capes at the mouth of the bay to Trenton, New Jersey, a distance of 135 miles. The portion of Delaware River between Trenton and the head of bay is referred to as the "river estuary" to distinguish it from the embayed portion (Delaware Bay) of the estuary.

Methods of Study

Approximately 140 samples of bottom sediment were obtained by means of a Shipex and harpoon sampler by the Philadelphia District, U. S. Army Corps of Engineers from locations in the Delaware estuary and tributary streams shown in Figure 3. In addition, 24 samples from the continental shelf in the vicinity of the capes were obtained from the Coastal Engineering Research Center and three beach samples off the Delaware coast were procured from the Geology Department of the University of Delaware. Most of the bottom samples were obtained in the summer of 1969; however,

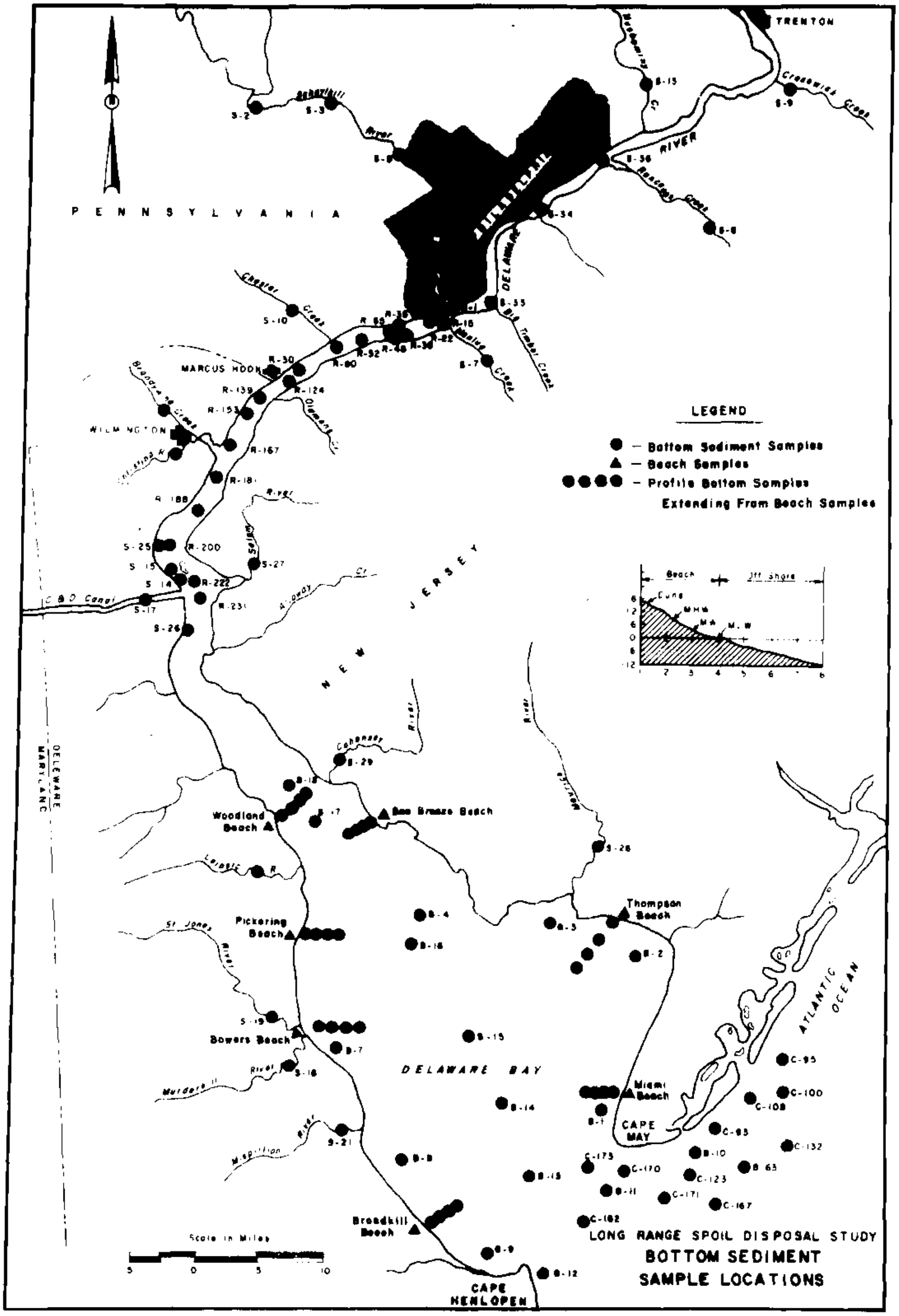
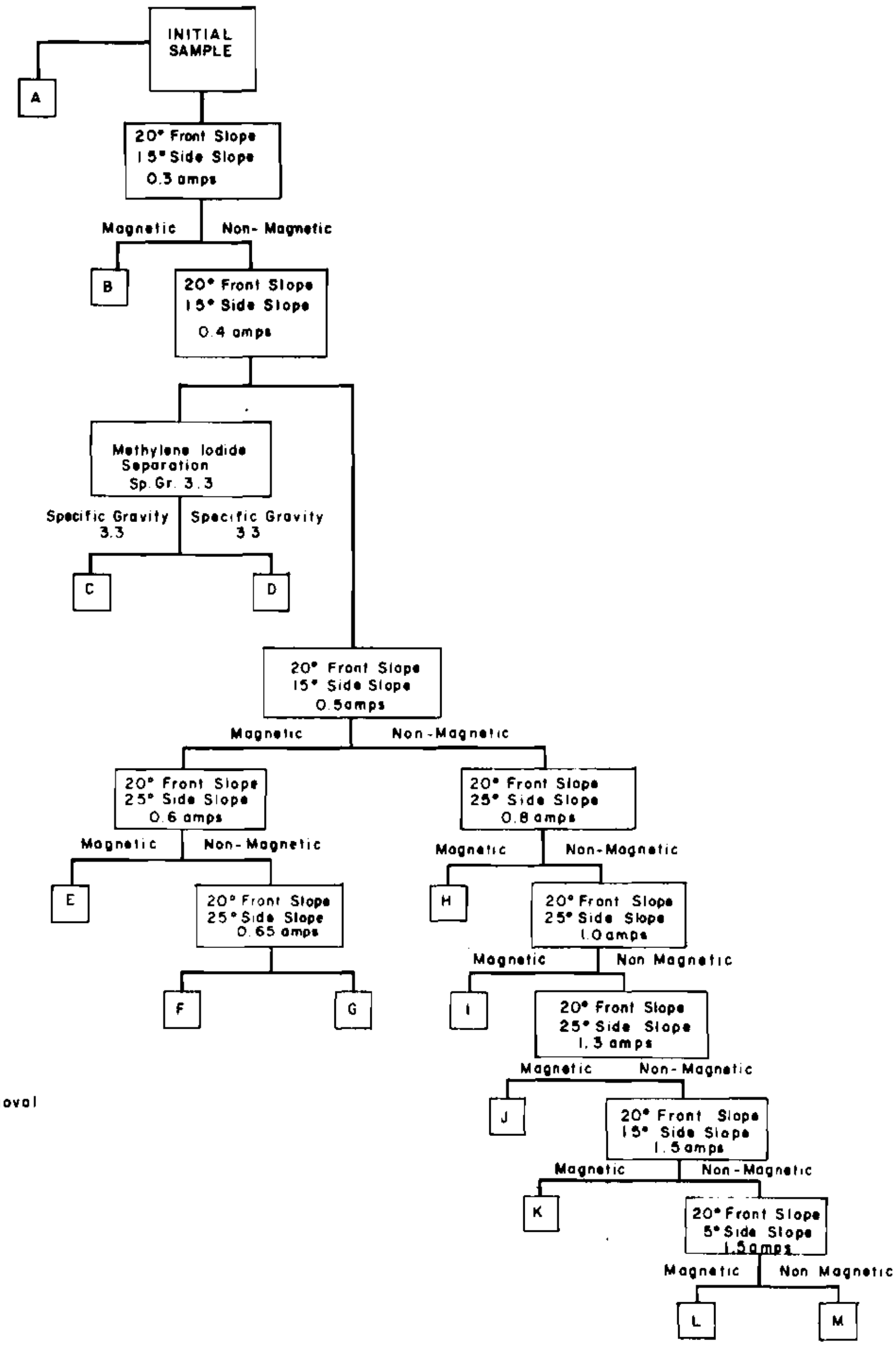


Figure 3. Location of Bottom Sediment Samples in Delaware Estuary and Vicinity

several shoal samples were collected periodically up to March 1972.

Separation of the heavy minerals of sand size from the rest of the bottom sediment was effected by standard techniques described by Folk (1968) and Krumbein and Pettijohn (1938). The sediments were wet sieved, to obtain the sand fraction. Bromoform (specific gravity equals 2.89) was used to separate a 25 gram sample of sand, representative of materials between 420 and 62 micron size, into the light and heavy components. A portion of the light fraction was set aside for identification by the binocular and petrographic microscope. The heavy fraction was sieved through a nest of +80, +100, and +200 sieves and the weight of each sieve fraction determined. Each fraction was mounted in 1.544 index oil, and the largest fraction mounted in Caedax (refractive index = 1.55), and identification made with a Bausch and Lomb Research Petrographic Microscope. Mineral frequency was obtained by a line counting method employing the Doeglas (1940) method; this method counts 100 grains, notes the percentage of opaques and mica, then continues counting until 100 transparent minerals have been identified and recorded. This is repeated three times for a statistical count. The method eliminates the masking effect of the more abundant opaques and focuses attention on the more diagnostic transparent minerals. Mica, in the transparent minerals, is eliminated from the count because its flaky shape causes an incomplete separation from light mineral grains. No distinction was made of ilmenite, opaque rutile, or hematite in the non-magnetic opaque heavy mineral fractions; however, the total percent of the magnetic and non-magnetic opaque fractions was recorded. Transparent species were given a weighted average for the individual sample and percentages appear in tables of Appendix A for sample locations shown in Figure 3.

In addition to the foregoing procedures, twelve samples were selected for analysis by means of the isodynamic separator and x-ray diffraction technique for corroborating heavy mineral identification. A flow sheet for the isodynamic magnetic separation is depicted in Figure 4; prior to analysis, magnetite was removed with a hand magnet. Utilizing the difference in magnetic susceptibility, it was possible to obtain separation of minerals difficult to analyze with the petrographic microscope. For example, actinolite with its higher iron content, was more susceptible to a magnetic force than was tremolite, which is rich in magnesium. It was found that, by setting the magnetic separator at a front tilt angle of 25°, the actinolite separated from the sample when 0.8 amp was passed through the magnet, but that it took 1.2 amps to attract the tremolite with the same front and side tilt angles. In the same manner, aggregates of sillimanite, which were difficult to identify, were readily separated by their lack of magnetic susceptibility since they contain no iron. Further separation of heavy mineral fractions was also effected by methylene iodide of 3.2 specific gravity. The weights of each fraction were recorded and the weighted percent of a pure mineral fraction obtained by this mineral beneficiating technique. X-ray diffraction analysis was accomplished on pure mineral fractions for verification of petrographic identification; in this process the complete representative sample was pulverized and passed through a 200 sieve and the powder press method of sample preparation accomplished before the minerals were scanned with x-rays at 2° 2θ per minute on a Phillips x-ray diffractometer unit with a copper target tube. The petrographic techniques and corroborative evidence



NOTES: 1. A is magnetite removal with hand magnet.

Figure 4. Isodynamic Magnetic Separator Flow Diagram for Heavy Mineral Analysis

from the isodynamic magnetic separator and x-ray diffraction presents a high degree of confidence to the heavy mineral identification as reported in this investigation.

Heavy Mineral Components and Stability Factors

Heavy Minerals

The heavy minerals of Delaware estuary and vicinity comprise between 0.3 and 15 percent of the sand fraction (62 to 420 micron size) with most values between one and four percent. Streams draining the crystalline rocks of the Piedmont formations were found to contain the higher values with a general average of nine percent heavy minerals.

Transparent heavy minerals (exclusive of mica) are more abundant than the opaque heavy minerals in all but a few tributary streams. The transparent heavy mineral species identified in the Delaware estuary include the following: hornblende, garnet, zircon, staurolite, epidote, sillimanite, tourmaline, augite, kyanite, hypersthene, rutile, actinolite, tremolite, diopside, apatite, chloritoid, zosite, sphene, and minor others. Four minerals -- hornblende, garnet, zircon, and sillimanite -- comprise between 70 and 77 percent of the transparent heavy mineral fraction in the estuary. The general description of the common transparent mineral species is given in the appendix.

Opaque heavy minerals were not studied in detail; however, their representation in each sample is listed in Table 4 of the Appendix. Examination of several samples revealed common opaque minerals such as ilmenite, magnetite, hematite, leucoxene, and limonite.

Stability Order of Transparent Heavy Minerals

Several interpretations regarding the stability of heavy minerals exist in the literature but few agree on relative degree on all. Groot and Glass (1960) published a list where common agreement regarding relative chemical stability of heavy minerals exists as follows:

Zircon Rutile Tourmaline	Very stable
Staurolite Kyanite Garnet	Moderately stable
Hornblende Augite	Least stable

To this list could be added several other heavy minerals and especially sillimanite which is placed in accordance with the findings of Neiheisel (1962, p. 371) and Dryden and Dryden (1946, p. 94) as one of the moderate to very stable minerals chemically but considerably less in rank on the scale of resistance to mechanical abrasion. Sillimanite remains persistent throughout the Delaware River estuary and Delaware Bay except in the vicinity of the capes. Sillimanite is especially important in this investigation where Delaware Bay sediments mix with the continental shelf sediments of considerable abrasive history and glacial origin.

Full versus Limited Heavy-Mineral Suite

Strom (1972) summarizes the various definitions and interpretations given the "full" and "limited" heavy-mineral suite given wide use by Owens and Sohl (1969) and others. In its most liberal usage the terms refer to the resistance of the heavy minerals to destruction by chemical agencies. Thus, a "full" heavy-mineral suite might contain some of the least stable of the heavy minerals previously described, i.e., augite and hornblende while the "limited" or stable heavy-mineral suite would contain only the more resistant heavy minerals such as zircon, rutile, and tourmaline and possibly some of the moderately stable mineral species but would be impoverished in less stable mineral species.

Thus, the Coastal Plain sediments older than Pleistocene contain the "limited" or stable heavy-mineral suite and the Piedmont source sediments contain the "full" heavy-mineral suite. This concept is important in relating source areas.

Textural Aspects

In any comparison with the heavy mineral studies conducted by previous investigators it is necessary to consider the similarity of size range of heavy minerals studied since some of the heavy minerals vary in proportional amounts with size. Most of the previous investigations by Jordon and Groot (1962), Groot and Glass (1960), Owens and Sohl (1969), and McMaster (1954) are in the 62 to 500 micron size range; Strom (1972) in the southwest Delaware Bay covers a variety of ranges. This investigation considers only those heavy minerals between 62 and 420 micron size and is thus comparable with most investigations.

CHAPTER II

GEOLOGIC SETTING

General

The geologic formations in the regional setting of the Delaware estuary are depicted in Figure 5. The Piedmont crystalline complex is comprised of Pre-Cambrian gneisses and greenstones, Paleozoic-Pre-Cambrian Wissahickan Schist and Baltimore Gneiss, Paleozoic folded and faulted sediments, and Triassic red and grey continental sands and shales with diabase sills. The Coastal Plain sediments consist of Cretaceous Formations near the Fall Line and Eocene, Miocene, and Quaternary sediments toward the coast. Blanket deposits of Pleistocene sediments cover most of the Coastal Plain and lower part of the Piedmont provinces.

The Delaware estuary is that portion of the Delaware River from the Fall Line at Trenton to the capes at the entrance to Delaware Bay. The Delaware River bends at nearly right angles at Trenton to an essentially parallel relation with regional structure, at the hinge between the Piedmont and Coastal Plain Provinces of contrasting lithologic units. The rather unique geologic setting of the Delaware River estuary along the Fall Line provides an ideal study area for controlled heavy mineral evaluations. The Piedmont crystalline rocks on the northwest side of the river estuary contribute a "full" heavy-mineral suite while the Coastal Plain sediments older than Pleistocene contain a relatively stable heavy-mineral suite. With evaluation of the heavy-mineral suite in the Delaware

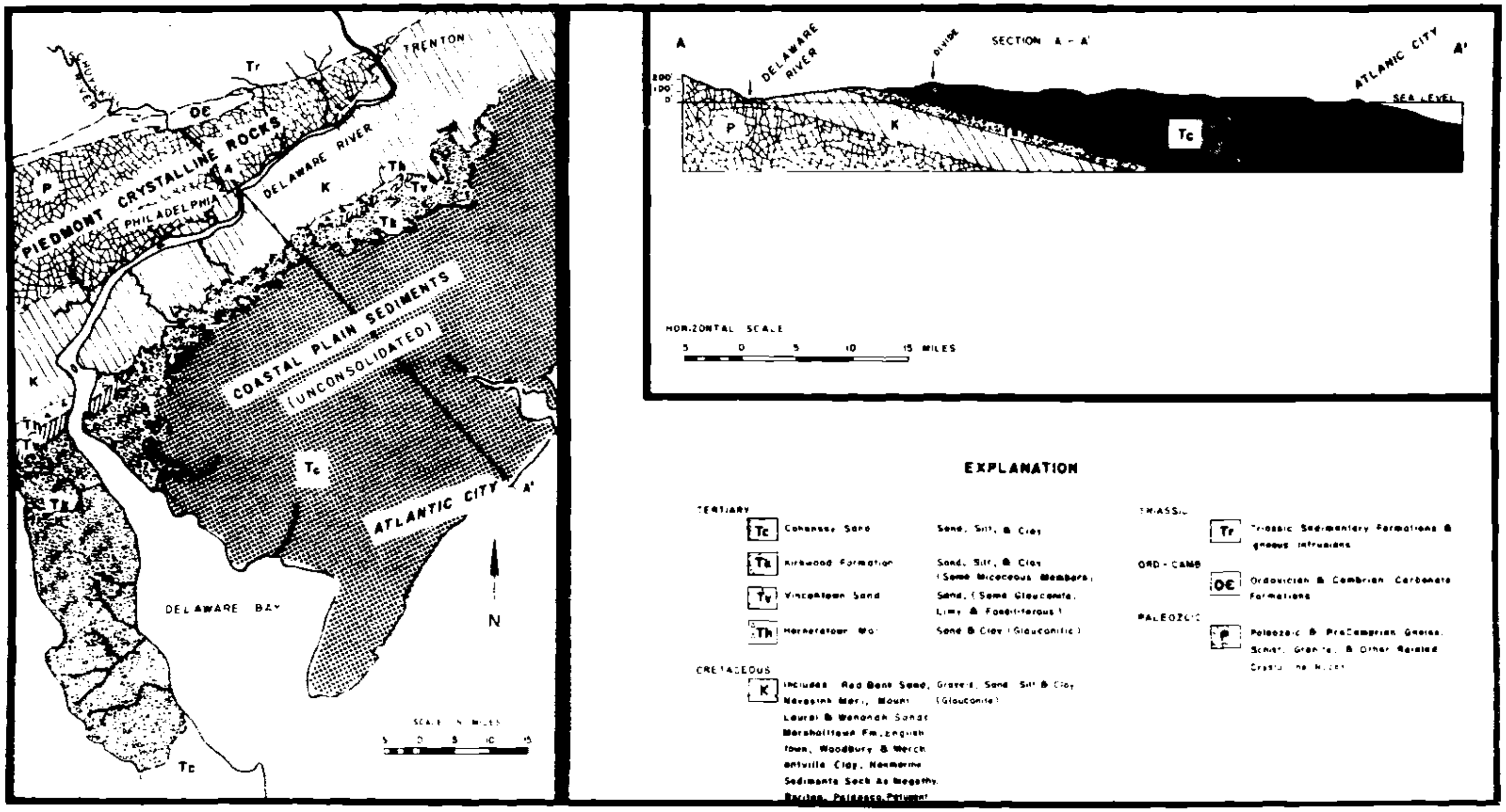


Figure 5. Generalized Geologic Map and Section of Delaware Estuary and Vicinity

River bottom sediment at Trenton and progressively along the river estuary, the influence of the contributing source is observed in the heavy-mineral suite. Analysis of the bottom sediments of the streams draining these contrasting sources of heavy minerals also provides basic data for evaluation. Stream gaging records by the U. S. Geological Survey and the U. S. Army, Corps of Engineers on sediment discharge when coupled with the heavy mineral analysis provide a quantitative means of determining the source of heavy minerals through the river estuary.

The embayed portion of the estuary constitutes Delaware Bay which receives discharge from Coastal Plain streams and is contained in a wedge of predominantly clastic sediments tapering from the surface at the Fall Line to 7,000 feet at the mouth of Delaware Bay (see Figure 5).

The Delaware estuary location within the physiographic boundaries indicated is a recent geologic event. As Schubel (1971) points out, positions of the present day estuaries are a consequence of the rise of sea level some 125 meters following the retreat of the last continental glacier approximately 18,000 years ago. Estuaries have had outlines approximating their present configurations for only the past few thousand years, but many of the deeper submerged river valley estuaries such as the Delaware River estuary, have occupied the deeper seaward portions of the same basins for 8 to 10,000 years. According to Kraft (1971), the Delaware estuary approximately 7,000 years ago occupied a position of a narrow river valley in the site of the lower end of the present Delaware Bay to a bay area extending more than 10 miles onto the present day continental shelf and 12,000 years ago the estuary was well out on the continental shelf.

The effect of the alternating regressions and transgressions of the sea during the Pleistocene is reflected in the sediments.

Heavy Minerals of Coastal Plain Formations

The heavy minerals in the Coastal Plain Formations of Delaware and New Jersey have been investigated by Owens and Sohl (1969), Jordan (1964), Groot (1955), and others. The investigators generally recognize the restricted or "stable" heavy-mineral suite of the Coastal Plain sediments older than Quanternary and the "full" heavy-mineral suite of the Pleistocene. The extensive investigation of the heavy minerals of the Cretaceous, Pleistocene, and Recent Formations of Delaware and New Jersey by Groot (1955) is listed in Table 1 and depicted graphically in Figure 6 along with the investigations of New Jersey Coastal Plain Formations by Owens and Sohl (1969). Jordan's (1964) analyses of 75 samples of the Pleistocene Formation of Delaware are listed below for heavy minerals between 62 and 500 micron size.

Heavy Minerals of Pleistocene FMS in Delaware
(after Jordan, 1964)

	Min	Max	Avg
Amphibole (hornblende)	0.0	69.0	13.8
Andalusite	0.0	2.0	0.4
Chloritoid	0.0	4.0	1.0
Epidote	3.0	45.0	17.6
Garnet	0.0	11.0	1.6
Kyanite	0.0	7.0	2.1
Pyroxene	0.0	6.0	0.5
Rutile	0.0	8.0	3.7
Sillimanite	1.0	30.0	12.7
Staurolite	0.0	23.0	4.3
Tourmaline	0.0	25.0	5.8
Zircon	3.0	62.0	33.6
Altered	0.0	7.0	1.9
Unidentified	0.0	4.0	1.5
Apatite, Sphene, Monazite, Spinel			Trace

Table 1. Concentration and Significant Heavy Mineral Fractions of the Heavy-Mineral Suites of Cretaceous, Pleistocene, and Recent Formations of Delaware

Heavy Mineral Species	Recent Fm Delaware	Pleistocene Fm Delaware	Upper Cretaceous Fm Red Bank Delaware	Mount Laurel Navesink Delaware-New Jersey		Wenonah Delaware	Merchantville Del.	N. J.	Upper and Lower Cretaceous Fm Patapsco-Raritan Del.	N.J.	Magothy Delaware	Patuxent Delaware	English-town New Jersey
			% Heavy Minerals in Sand Fraction - Range and Average										
Heavy Mineral	-	-	1-2 1	Tr-5 2		Tr-2 1	Tr-3 1		Tr-3 Tr		1-13 2	Tr-3 2	-
			% Mineral Species in Transparent Heavy Mineral Fraction - Range and Average										
Hornblende	1-39 10	1-37 8	1-2 1	1-5 2	Tr-2 Tr	Tr-1 1	Tr-1 Tr	- -	Tr-1 1	- -	Tr-1 Tr	Tr-2 1	Tr-1 1
Staurolite	1-17 7	2-22 8	20-34 26	2-28 13	24-29 26	4-14 11	6-20 9	7	1-14 3	9-16 12	22-80 59	24-83 50	19-20 19
Garnet	1-17 3	1-6 2	1-4 2	2-22 12	Tr-1 Tr	1-11 3	2-18 14	8	Tr-1 Tr	Tr Tr	Tr-1 Tr	Tr-1 Tr	- -
Zircon	1-40 10	1-52 16	1-7 5	3-22 12	5-7 6	2-16 10	2-19 10	14	17-48 33	16-18 17	1-24 9	1-2 1	5-12 8
Epidote	3-21 9	1-25 13	15-25 19	13-26 19	13-24 18	15-38 24	10-28 22	18	1-2 1	1-2 2	Tr-1 Tr	1-2 1	Tr-3 1
Tourmaline	1-18 7	1-11 5	6-16 10	4-14 9	4-10 7	5-16 10	3-12 8	13	4-19 9	4-15 10	3-27 12	3-28 13	12-20 16
Sillimanite	1-17 7	1-22 8	2-9 5	1-5 3	4-5 4	1-7 3	1-5 2	-	Tr-1 1	- -	Tr-1 1	Tr-1 1	11-12 11
Kyanite	1-6 3	1-11 6	3-10 7	1-7 3	4-6 5	1-5 3	1-7 2	2	Tr-1 1	Tr-3 2	1-7 3	1-17 6	7-8 7
Rutile	1-5 3	1-12 5	5-12 8	4-18 10	4-12 8	6-16 11	4-14 10	9	4-21 12	1-6 4	1-14 4	1-18 5	10-12 11
Hypersthene	1-3 2	1-12 4	-	-	-	-	-	-	-	-	-	-	-
Clinopyroxene	1-5 2	1-16 3	-	-	-	-	-	-	-	-	-	-	-
Chloritoid	1-2 1	1-5 2	2-7 4	1-12 6	5-6 5	7-15 10	4-15 10	22	- -	- -	Tr-1 Tr	- -	- -

Notes: 1. Heavy mineral fractions of key minerals in the Cretaceous, Pleistocene, and Recent formations of Delaware and New Jersey Coastal Plain Formation compiled from data by Groot (1955).

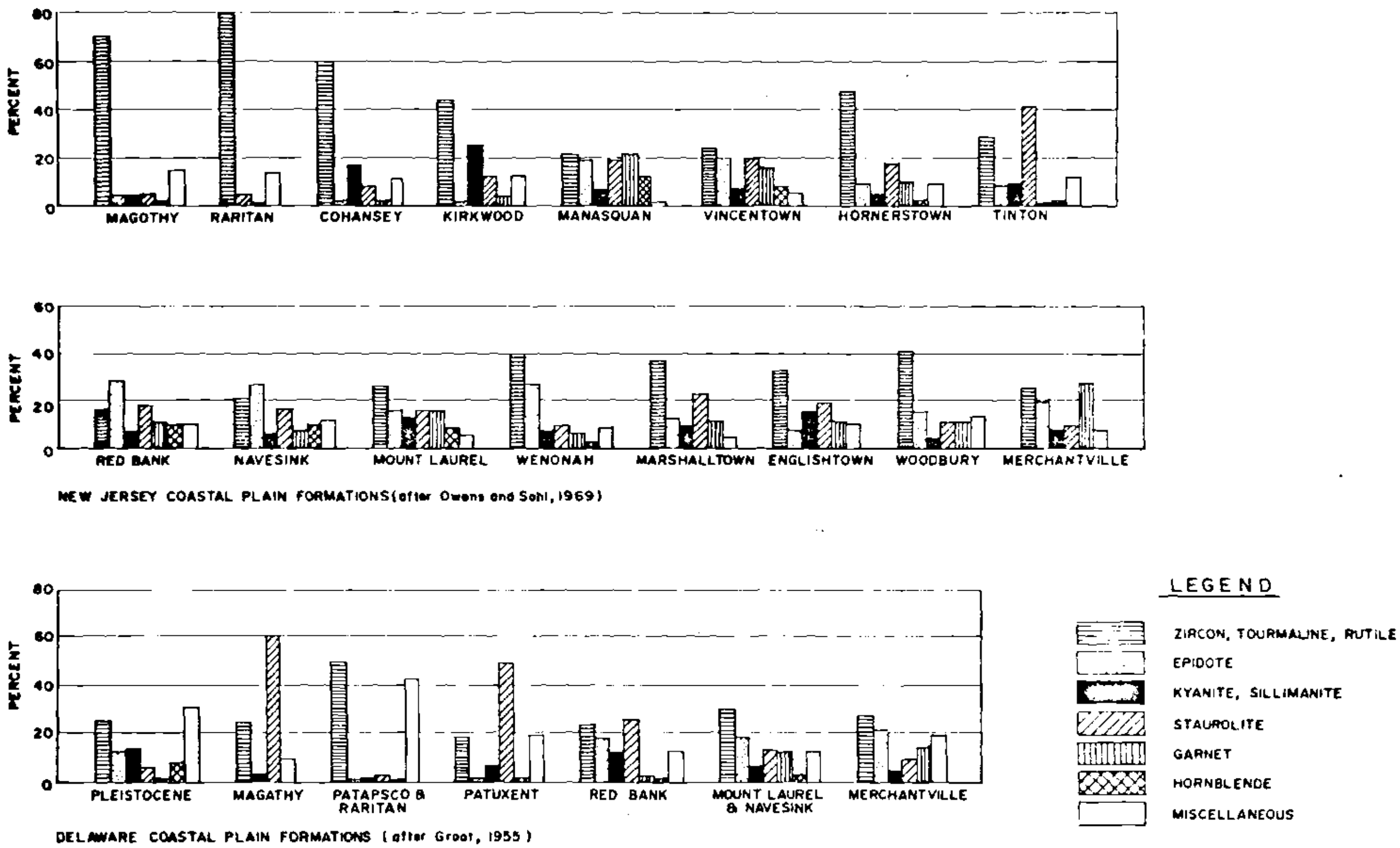


Figure 6. Bar Graph Diagram of Sand-Size Transparent Heavy Mineral Distribution in New Jersey and Delaware Coastal Plain Formations

The Pleistocene heavy mineral suite of Jordan (1964) shows a varied suite of heavy minerals in which zircon, epidote, amphibole (mostly hornblende), and sillimanite are the most abundant species. In his analysis Jordan (1964) showed that zircon and hornblende averaged 34 and 14 percent, respectively, but were the minerals which had major variations ranging from extreme zero to values in excess of 60 percent. Sillimanite in the Pleistocene sands ranges between 1 and 30 percent with an average of 12.7 percent for 75 samples; this is somewhat higher than that reported by Groot (1955) who shows a range between 1 and 22 percent and an average of eight percent sillimanite (see Table 1). The heavy mineral suite described by Jordan (1964) generally resembles that indicated by the 25 samples from Delaware Pleistocene sands published by Groot (1955); notable differences are higher zircon and less hornblende and greater consistency of the suite by Groot (1955).

Heavy Minerals of Piedmont Crystalline Rocks

The Piedmont crystalline rocks are comprised of gneiss and schist formations with a relative abundant source of hornblende and garnet. The Paleozoic-Pre-Cambrian Wissahickon Schist is an especially abundant source of garnet. Diabase sills locally constitute a source of pyroxene. Hornblende is especially rich in gneiss outcrops. Dryden and Dryden (1946) site pink zircon as characteristic of the Wissahickon Schist of southeastern Pennsylvania and Moxley (1970) reports this mineral in samples on the Delaware side of the estuary.

Of special importance is the relatively "clean" surface of Piedmont rocks, free of Pleistocene blanket deposits, between Trenton and the state of Delaware on the Piedmont drainage area considered in this investigation. This is clearly shown on Pleistocene maps of the area and by Kraft and Maisano (1969) on the map of the geology of the middle Atlantic Coastal area.

Previous Heavy Mineral Investigations in Delaware Estuary

Although knowledge of the heavy minerals of the Coastal Plain formations of Delaware and New Jersey is abundant and based on several investigations and the heavy minerals of the New Jersey coastal area and continental shelf sands are generally well known, the analysis of heavy minerals in bottom sediment between Trenton and the vicinity of the capes prior to this investigation was limited to one core sample in the Delaware River south of Wilmington described in an excellent manner by Jordan and Groot (1962). Several heavy mineral samples of a reconnaissance nature were reported for the Delaware Bay during the progress stages of this investigation by Strom (1972) and Moxley (1970) and, although limited in scope, provide corroborative evidence of heavy mineral types.

The heavy minerals in this investigation were studied in three phases: (1) Delaware River from Trenton to the bay and tributaries from both the Coastal Plain and Piedmont sources, (2) Delaware Bay to the capes including beach profile and bottom sediments, and (3) the coastal offshore areas of the continental shelf fronting the Delaware capes. Special attention was given the quantities of sediments being considered from the various sources and the hydrodynamic agencies which affect transport of the sediment.

CHAPTER III

PHYSICAL AND HYDRODYNAMIC CHARACTERISTICS OF DELAWARE ESTUARY

General

Any consideration of the source and transport characteristics of heavy minerals from the source areas must be preceded by a general description of the physiographic unit comprising the watershed and the nature of the hydrodynamics of the estuary. The physical characteristics of the Delaware estuary are depicted graphically in Figure 2 and the bathymetry of the bay, tidal currents, and prevailing winds are shown in Figures 7, 9, and 10.

The total distance of Delaware estuary has a length of about 133 miles measured along midstream, a width at the mouth of about 11 miles, and a maximum width (about 12 miles above the mouth) of about 26 miles, and a minimum width at the head of tide of 800 feet. Upstream of the point of maximum width, the width decreases at a fairly uniform rate; it may be said that this estuary has the classic funnel shape that is characteristic of many estuaries. Its geometry is relatively simple in other respects. There are few islands having significant back channels, and therefore most of the flow is concentrated in one main channel. The cross-sectional geometry is such that it varies from a maximum at the point of greatest width to a minimum at the head of tide with rather remarkable uniformity. Figure 2 shows these characteristics.

In the downstream 60 miles of the estuary, the shoreline is marshy on both sides of the waterway and these marshes often extend considerable distances inland (see Figure 7). Above mile 60, marshes are sometimes found along both shorelines while at other places there is relatively high ground. The bed of the estuary is mostly fine to coarse sand in the middle half and generally soft muds in the quarters along the shore, from the mouth to about mile 40. From mile 40 to mile 95, the bottom consists mostly of silt-size materials, although there are a few areas where fine sands are encountered. In the reach from mile 79 to mile 84 there are outcroppings of gneisses and schists along the westerly side. From mile 95 to mile 102, the materials encountered include some sands but mostly compact fines, and there is another outcropping of gneisses and schists near the upper end of this reach. From mile 102 to the head of tide, the bottom is composed of mud, sand, and gravel, and there is a reach extending from mile 111 to 116 where the schists and gneisses again appear.

Fresh Water Discharge from Watershed

The total drainage area tributary to the estuary amounts to 12,765 square miles, excluding 782 square miles of water surface in the estuary (see Figure 8). The inferred total average annual inflow of fresh water, head of tide to the mouth, is 20,200 cfs; this is based on recording gage data governing the three major parts of the drainage area over long periods, and similar data for eight smaller tributaries during shorter periods. The following tabulation gives some detail on the geographic distribution of the drainage area and the fresh water inflows.

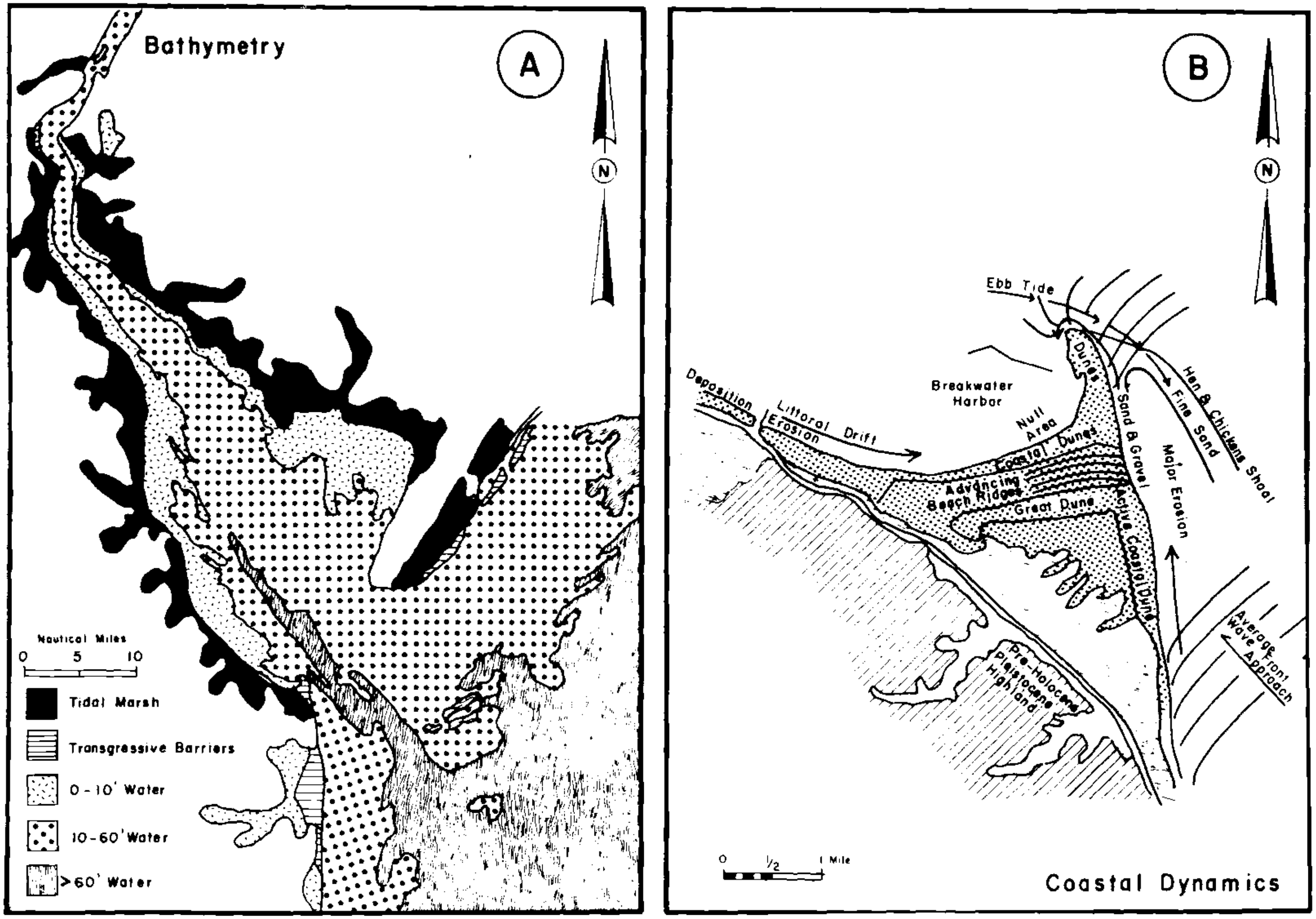
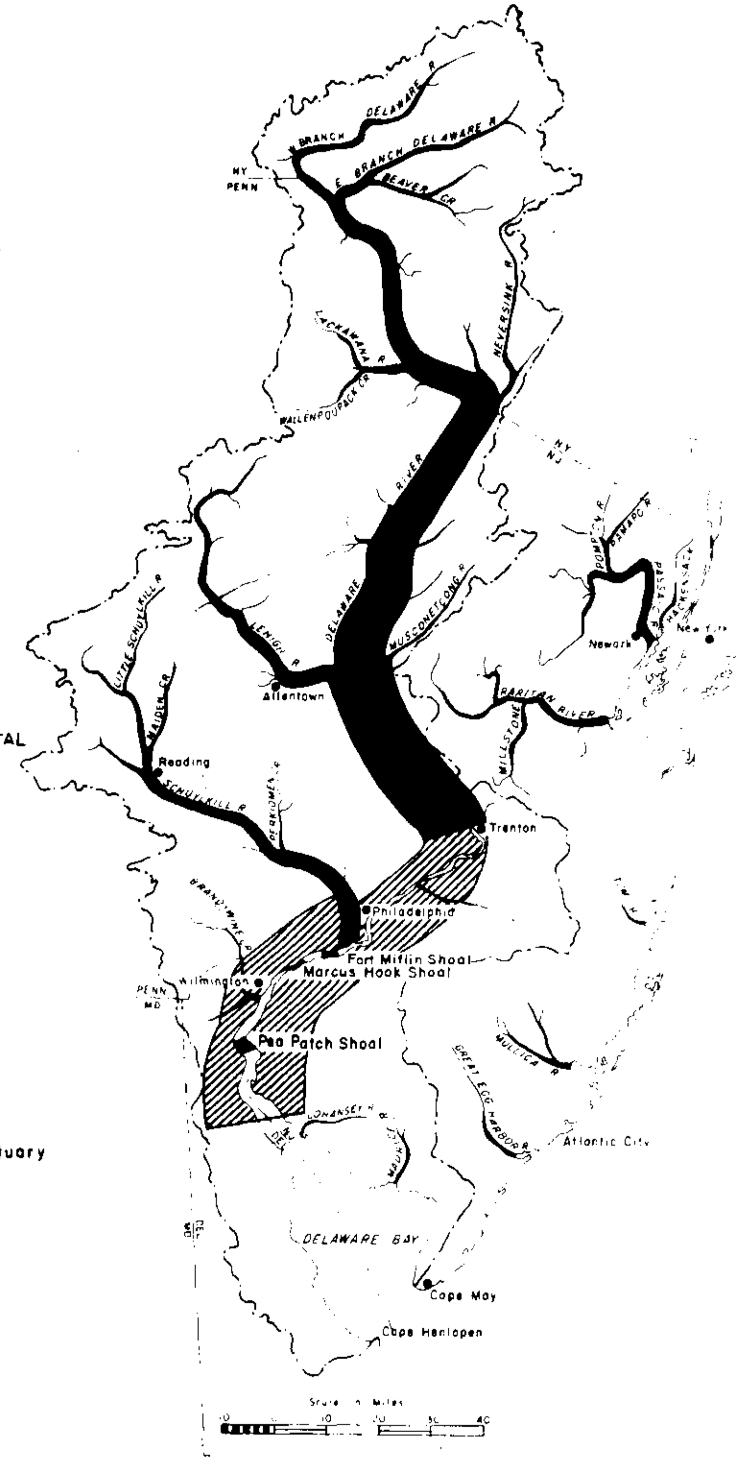


Figure 7. (A) Bathymetry of Delaware Estuary and Atlantic Coast and (B) Coastal Dynamics in Vicinity of Cape Heniopen (after Kraft (1971))

DELAWARE WATERSHED

Drainage Area (Sq. Miles)	Sediment (Ann. Tons)
Headwaters Delaware River to Trenton	
6,780	770,000
Trenton to Schuylkill River	
3,208	354,500
Schuylkill River to Christina River	
950	131,900
Christina River to Cohansey River	
622	43,500
Delaware Bay Cohansey River to Capes	
1,205	101,800
12,765	1,401,700 TOTAL



LEGEND

Delaware River Estuary

Major Shoal Areas

Average Discharge

Discharge Cubic Feet Per Second

Figure 8. Delaware River Watershed Showing Annual Discharge to the Estuary and Location of Major Shoals

Source of Inflow	Location, Miles above Mouth	Drainage Area Sq. Mi.	Drainage Area % of Total	Average Annual Inflow cfs	Average Annual Inflow % of Total
Delaware River at Trenton	133	6,780	53.1	12,000	59.4
Intermediate small tributaries	---	1,300	10.2	1,810	9.0
Schuylkill River at Philadelphia	93	1,909	15.0	2,750	13.6
Sub-Totals	93	(9,989)	(78.3)	(16,560)	(82.0)
Intermediate small tributaries	---	464	3.6	650	3.2
Christina-Brandywine near Wilmington	70	569	4.5	750	3.7
Sub-Totals	70	(11,022)	(86.4)	(17,960)	(88.9)
Intermediate small tributaries	---	1,743	13.6	2,240	11.1
Totals at Mouth	0	12,765	100.0	20,200	100.0

The tabulation shows that most (88.9 percent) of the fresh water inflow enters the estuary in its upper 63 miles (47 percent of the total length). It also shows that the discharge per square mile is greatest from that part of the watershed located above the head of tide at Trenton (see Figure 8).

The maximum observed discharge of the Delaware at Trenton was 329,000 cfs and the minimum was 1,220 cfs. The maximum and minimum discharges of the Schuylkill were 96,200 cfs and 284 cfs, respectively. When these discharges are compared with the long-time mean values of 12,000 cfs and 2,750 cfs for these two principal points of entry of fresh water, it is apparent that the estuary receives a widely varying inflow of fresh water.

Tidal Regimen of Delaware Estuary

The tides of the Delaware Estuary are semidiurnal; there are two nearly equal high waters and two nearly equal low waters per lunar day. The mean range at the mouth is about four feet and the variation of elevation with time plots as a curve closely approximating a sine curve. As this tidal undulation propagates up the estuary, its range and the durations of rise and fall change with distance from the mouth. The range of tide increases as the distance from the mouth increases and the shape of the curves departs from the near sine curve plot at the mouth to a much distorted configuration at the head of tide; at head of tide a maximum of nearly seven feet is realized.

The maximum ebb and flood tidal current speed and direction from the Tidal Current Atlas for Delaware Bay, U. S. Coast and Geodetic Survey (1960) is shown in Figure 9. In general, it is observed that the currents are stronger on the New Jersey side of the lower bay (190 cm/sec), and decrease towards the shores (60 cm/sec) because of increased bottom friction on the mud flats. Current speeds are also observed to decrease where the bay widens and to increase where the bay converges (see Figure 9). According to Oostdam (1971) currents in the lower part of Delaware Bay consist almost entirely of tidal currents; this is based on average river discharge of 11,400 cfs at Trenton but even record discharge conditions in Delaware River would not influence the velocity appreciably. In a section across Delaware Bay, Oostdam (1971) showed that tidal currents were strongest in the center part of the bay (see Figure 10). Oostdam (1971) also

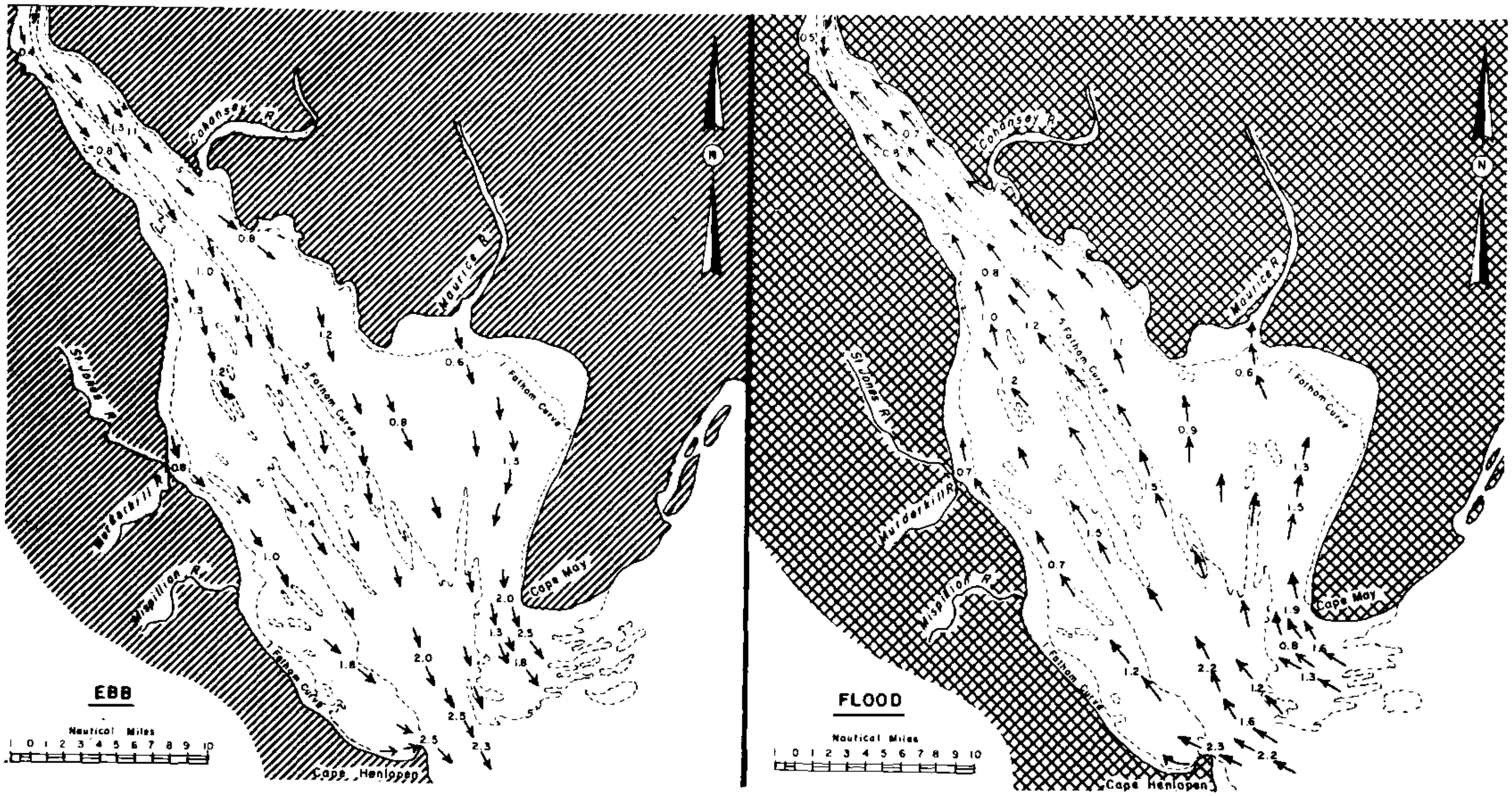


Figure 9. Maximum Ebb and Flood Tidal Current Speed and Direction in Delaware Bay (after Coast and Geodetic Survey (1960))

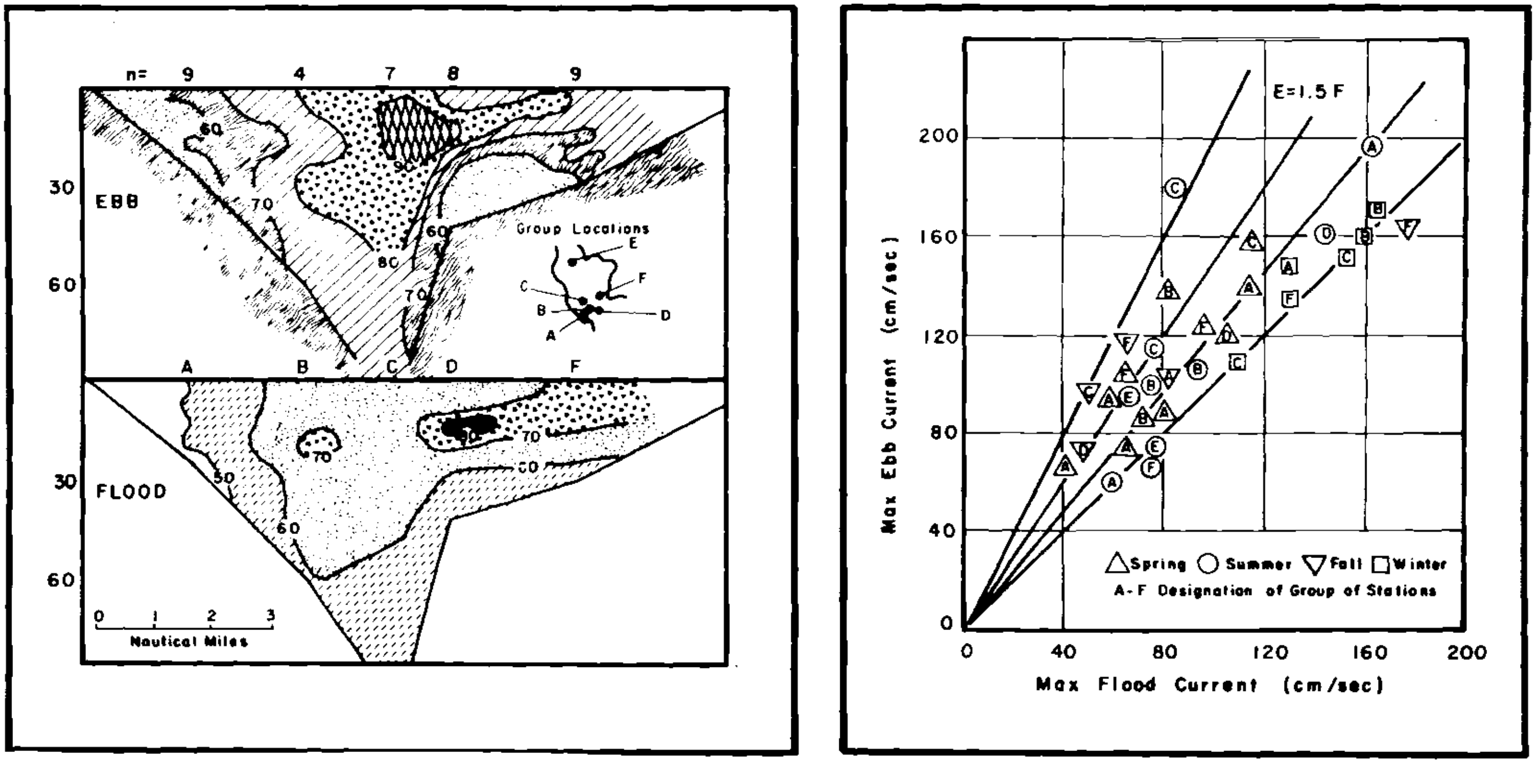


Figure 10. Mean Currents Across Delaware Bay and Comparison of Maximum Current Speeds for Ebb and Flood (after Oostdam (1971))

demonstrated that average values for current speeds in the bay were 67.6 cm/sec for ebb and 56.5 cm/sec for flood, so that ebb currents were on the average 20 percent faster than flood currents. Ebb currents usually reached their maximum speed towards the middle of the tidal half cycle and in the upper third of the water column, and flood currents commonly reached their maximum speed within two hours after low water slack and in the bottom half of the water column. The average ebb current lasted six hours twenty-seven minutes and the average flood five hours fifty-seven minutes (Oostdam, 1971).

Salinity Aspect

The salinity of the waters of the Delaware Estuary at any given point at any given time is the result of a complex relationship between the salinity of the Atlantic Ocean at the mouth, the upland flows, and the tidal discharges. The mean salinity at the mouth of the estuary is 28.8 parts per thousand (ppt). With several weeks or more of sustained upland flows at or near the mean value, the upper limit of brackish water at high water slack is at mile 75. During a prolonged drought, the upper limit of brackish water has intruded as much as 110 miles above the mouth.

Bathymetry of Bay Area

The maximum depth of Delaware Bay is 151 feet and occurs along ancestoral Pleistocene drainage lines toward the mouth of the bay. The average mean depth of the bay is 31.7 feet (see Figure 7A). The principal features of the bathymetry at Delaware Bay include the following: (a) shoals off Cape May point, (b) series of shoals parallel to the axis of the bay and separated from each other by finger-like channels (see Figure 9), (c) shallow mud-flats which fringe most of the bay shore, and (d) the central channel which maintains depths in excess of 40 feet. The locus of the deepest points in the lower bay lies on the western (Delaware) side and does not coincide with the navigation channel (see Figure 7A).

Wind and Swell in Delaware Bay

Pronounced wind waves and swells in Delaware Bay are common in the late fall, winter, and early spring associated with storms. Hindcast methods by Corps of Engineers (1959) report waves as high as 15 feet in the breaker zones near the capes but in Delaware Bay waves of six to seven feet maximum are rarely experienced and four foot waves occur about once a year. Within Delaware Bay, winds from the NNW, NNE, and SSE present optimum fetch conditions. As a result of this wave energy, Oostdam (1971) has concluded that fine sediments are eroded from the channels in the central part of the bay and from the shores, while marine sands are deposited in the bay mouth area and possibly on the elongated shoals of the bay.

CHAPTER IV

HEAVY MINERALS FROM TRIBUTARY STREAMS

The annual tons of heavy minerals discharged from Piedmont and Coastal Plain streams along the course of the Delaware River estuary are listed below for the various source areas.

Stream and Drainage Area	Drainage Area (Sq. Mi.)	Annual Sediment Discharge (tons)	Annual Heavy Minerals (tons)	Annual Transparent Heavy Minerals (tons)
Delaware R. - Piedmont at Trenton App. Highlands	6,780	770,000	3,080	1,786
Crosswick Cr. - Coastal Plain	385	25,100	30	7
Neshaminy Cr. - Piedmont	233	45,100	185	94
Rancocas Cr. - Coastal Plain	385	19,000	68	22
Pennypack Cr. - Piedmont	132	22,400	37	15
Cooper River - Coastal Plain	159	11,900	24	10
Schuylkill R. - Piedmont and Valley & Ridge	1,916	231,000	693	243
Mantua Creek - Coastal Plain	51	2,800	8	1
Chester Creek - Piedmont	335	73,794	442	234
Christina R. - Coastal Plain	284	27,000	137	64
Christina R. - Piedmont	284	27,000	137	64
Salem River - Coastal Plain	452	32,300	32	12
Smyrna River - Coastal Plain	64	11,450	11	4
Cohansey R. - Coastal Plain	106	11,560	22	5
Maurice R. - Coastal Plain	388	11,948	26	18
St. Jones R. - Coastal Plain	90	12,038	12	3
Murderkill R. - Coastal Plain	96	12,134	4	1
Mispillion R. - Coastal Plain	126	12,260	23	13

The streams are designated as a Coastal Plain or Piedmont source area and sediment discharge obtained from U. S. Army, Corps of Engineers Records (1969). The percent heavy minerals listed is based on the testing of the bottom sediment sand fraction between 62 and 420 micron size.

The sand fraction of the sediment discharge is a statistical estimate, based on U. S. Geological Survey (1967) computations that approximately 10 percent of the sediment discharge is sand size material. The annual tons of heavy minerals listed is the product of the percent heavy minerals and the annual tons of sand. The annual tons of transparent heavy minerals is the fractional amount of this material determined by sample analysis (see Table 4, Appendix A). The amount of transparent heavy minerals in the sand fraction delivered to the Delaware River between Trenton and the bay from the tributary streams is estimated at 1494 tons annually from Piedmont streams and 310 tons annually from Coastal Plain streams; thus the Piedmont source streams of contrasting heavy-mineral suite delivers five times the amount of transparent heavy minerals to the Delaware River compared to the Coastal Plain streams.

CHAPTER V

ANALYSIS OF HEAVY MINERAL DISTRIBUTION PATTERNS IN DELAWARE ESTUARY

Introduction

The systematic analysis of more than 140 bottom sediment samples for the transparent heavy minerals (between 62 and 420 micron size), in station locations from Trenton to the vicinity of the capes, has established data reflecting upon source and transport characteristics of sand-size sediments in the estuary and at the interface with continental shelf sediments. Definite heavy mineral provinces were found in this investigation to exist in the estuary. The river estuary is dominated by a fluvial Piedmont source with a "full" heavy-mineral suite characterized by hornblende and garnet while the major portion of the embayed estuary has a large mixed fluvial Piedmont and Coastal Plain heavy-mineral suite described as the Delaware Bay province and characterized by sillimanite and generally "full" heavy mineral suite. A smaller heavy mineral province occurs in the lower eastern and lower central sections of the bay as a result of the mixing of the bay and continental shelf sands in the lower eastern bay area in the vicinity of the capes.

The heavy minerals in this investigation were studied in three phases: (1) Delaware River from Trenton to the bay and tributaries from both the Coastal Plain and Piedmont sources, (2) Delaware Bay to the capes including beach profile and bottom sediments, and (3) the coastal and offshore areas of the continental shelf fronting the Delaware capes. Special attention is given the quantities of sediments being considered from the various sources and the hydrodynamic agencies which affect transport of the sediment.

Heavy Mineral Suite of Tributary Streams

The heterogeneous nature of the Piedmont crystalline rock and variability of heavy minerals within formations of Coastal Plain sediment points out the need for a measure of quantity and composition of each heavy mineral suite from discharge points of rivers tributary to the Delaware River as well as at regular intervals along the Delaware River between Trenton and the bay. Heavy minerals analysis of bottom sediment from streams draining the major Piedmont and Coastal Plain is listed in Table 4 of Appendix A for locations shown in Figure 3 and shown graphically in Figure 11. A summary of the heavy minerals from source areas and locations within the estuary is presented in Table 2.

In an earlier section it was demonstrated that the Piedmont streams between Trenton and the capes annually deliver approximately five times the annual tonnage of heavy minerals to the river estuary; the Piedmont streams deliver approximately 1500 tons annually and Coastal Plain streams about 310 tons annually. The heavy mineral content of the Piedmont streams ranges between three and six percent in the sand fraction of estimated sediment discharge; these data and percents opaque versus transparent heavy minerals are listed in Table 4 of Appendix A for individual sample locations.

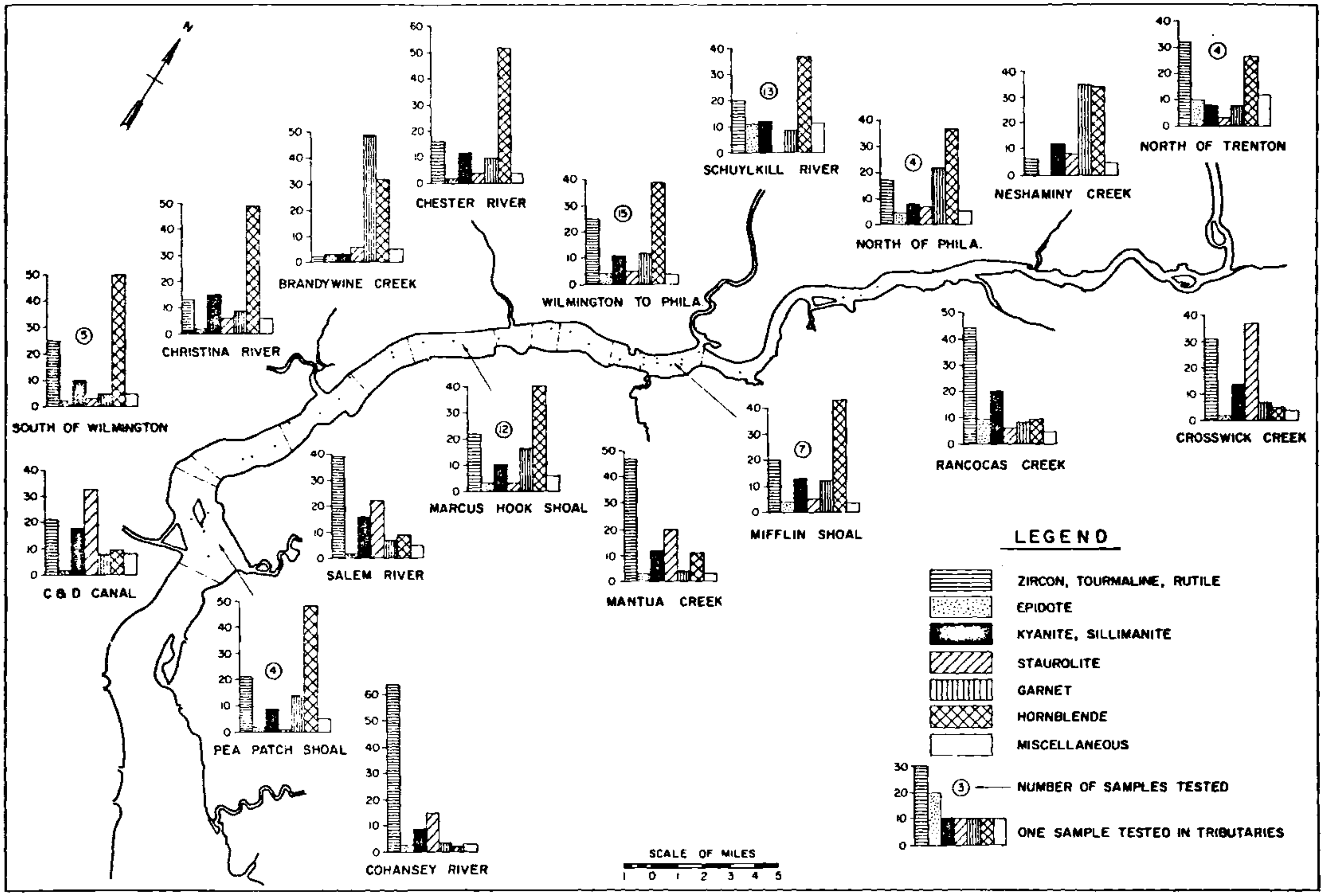


Figure 11. Composition of Transparent Heavy-Mineral Fraction of Delaware River and Tributaries

Table 2. Summary of Heavy Mineral Distribution in Delaware Estuary, Delaware Bay, and the Continental Shelf

Heavy Mineral Species	Delaware River Tributaries: Delaware R. North of Trenton	Schuyl-kill River	Piedmont Tribu-taries	Coastal Plain Rivers	Delaware Estuary: North of Phila-delphia	South of Phila-delphia	Average Total Bay	Delaware Bay: Delaware West Side of Bay	New Jersey East Side of Bay	Vicinity of Capes: Delaware Bay near Cape May	Delaware Bay near Cape Henlopen	Continental Shelf: New Jersey Coastal Shelf	Delaware Coastal Shelf
	% Heavy Minerals in Sand Fraction - Range and Average												
H.M. Suite	3-6	2-5	3-15	Tr-5	1-3	Tr-7	Tr-18	Tr-18	1-6	1-4	1-5	Tr-8	1-3
	4	3	9	2	2	3	3	4	3	2	2	2	2
	% Mineral Species in Transparent Heavy-Mineral Fraction-Range and Average												
Hornblende	24-36	33-45	29-54	2-28	24-52	28-51	5-59	8-46	5-59	31-53	13-55	21-55	27-30
	27	37	40	10	37	38	28	28	23	42	31	34	28
Staurolite	1-8	Tr-2	Tr-8	4-37	3-10	1-8	Tr-26	Tr-21	3-26	Tr-12	2-23	3-18	6-16
	3	1	5	17	7	4	7	6	9	5	13	8	11
Garnet	6-15	7-12	9-49	3-11	16-38	6-16	2-34	3-34	2-20	6-22	6-24	12-27	10-19
	8	9	22	6	22	12	12	14	8	14	18	19	16
Zircon	6-32	8-14	1-11	18-59	6-22	8-33	5-50	6-50	5-48	6-12	8-15	9-25	5-15
	26	11	7	31	12	16	20	25	23	9	11	15	12
Epidote	9-15	9-14	Tr-11	2-14	2-5	1-8	1-20	5-14	1-20	5-7	6-9	3-7	5-8
	10	11	4	5	4	4	7	7	7	7	8	5	6
Tourmaline	2-3	4-6	Tr-6	2-9	2-4	1-4	1-7	1-5	1-7	2-7	1-5	2-5	2-5
	2	6	2	4	3	3	3	3	4	3	3	3	4
Sillimanite	4-8	4-10	3-13	6-16	3-9	6-12	3-34	3-34	5-20	5-13	6-8	2-7	2-13
	7	7	8	11	6	8	10	11	13	8	7	3	8
Kyanite	Tr-1	3-6	Tr-5	2-7	1-2	1-5	Tr-4	Tr-3	1-4	Tr-5	1-4	1-6	2-3
	1	5	3	4	2	3	2	1	2	2	3	2	3
Rutile	2-5	1-4	1-3	2-7	1-3	1-4	1-6	1-4	1-6	Tr-1	Tr-2	1-4	2-3
	4	3	2	4	2	2	2	2	3	1	1	2	2
No. Samples	4	13	4	10	4	20	43	16	13	4	4	15	4

NOTES:
1. Delaware River N. of Trenton based on 4 bottom samples; Schuylkill River based on 13 samples from N. Fairmount L&D Reservoir; Piedmont tributary streams comprise the Schuylkill River, Neshaminy Creek, Chester River and Brandywine Creek with each river given equal weight distribution; Coastal Plain tributary streams comprise Mantua Creek, Rancocas Creek, Crosswick Creek, Murderkill River, St. Jones River, Mispillion River, Salem River, Maurice River, Cohansey River and C&D Canal.
2. Delaware River samples North of Philadelphia comprised of 4 sample locations and other locations South of Philadelphia to St. Johns Light comprised of 20 samples.
3. Delaware Bay based upon 43 samples (28 along profiles of nearshore locations) over entire bay. Delaware side of bay includes profile locations and B-6 thru B-9 (20 samples), New Jersey side of bay includes profiles and B-1 thru B-5 (17 samples).
4. West side of bay (vicinity of capes) includes field samples B-8, B-9, B-12, B-13, and east side of bay inculdes field samples B-1, B-10, B-11, and B-14.
5. New Jersey continental shelf samples include locations C-93, C-95, C-100, C-108, C-123, C-132, C-152, C-167, C-170, C-171, and C-183 while Delaware continental shelf locations include C-182, C-183, B-12, and average of 3 Rheoboth Beach samples.

The drainage area of the headwaters of the Delaware River to the estuary at Trenton comprises an area of 6,780 square miles. In order to obtain an index to the heavy-mineral suite from such a large contributing source, four samples were obtained from bottom locations above the head of tide in the Delaware River. The average of the transparent heavy minerals from this location is 27 percent hornblende, 26 percent zircon, 10 percent epidote, 8 percent garnet, 7 percent sillimanite, 4 percent rutile, 3 percent staurolite, 2 percent tourmaline, 2 percent hypersthene, 2 percent augite, 2 percent tremolite, 2 percent actinolite, 1 percent kyanite, and 4 percent other minor miscellaneous mineral species (see Table 2). Any marked change in this heavy mineral suite in the Delaware River between Trenton and the bay may be attributed to the contributions from the discharge of streams draining the Piedmont formations on the northwest and streams draining the Coastal Plain formations on the southeast side of the estuary (see Figure 3).

Heavy Mineral Analysis of Delaware River

The Piedmont streams discharging into the river estuary between Trenton and the bay contribute a high ratio of garnet and hornblende (see Figure 11).

Analysis of the changes occurring in the heavy-mineral suite for the 70 mile distance of the river estuary between Trenton and Ship John at the head of the bay is summarized as follows:

a. Hornblende increases from 27 to 44 percent in a seaward direction as a result of Piedmont source sediments rich in this mineral effecting this increase. Chester Creek, for example, contains a heavy mineral suite in which hornblende comprises 51 percent of the transparent heavy mineral fraction.

b. Garnet increases from 8 to 12 percent in a seaward direction with the Piedmont source streams effecting this increase. Brandywine Creek which discharges into the Christina River at Wilmington harbor, contains 50 percent garnet in its transparent heavy-mineral suite which is a maximum garnet source area.

c. Zircon decreases from 26 to 16 percent and rutile decreases from 4 to 1 percent in a seaward direction. Despite the relatively high proportion of these stable minerals contributed to Coastal Plain streams, the higher quantity of Piedmont source heavy minerals effects a lower ratio in the river estuary sediment than exists at Trenton. Zircon, for example, averages 31 percent of the heavy-mineral suite of the Coastal Plain streams and 7 percent of the Piedmont streams for the distance from Trenton to the bay.

d. Tourmaline, also one of the most stable heavy minerals, increases from 2 to 3 percent in a seaward direction. This increase is attributed to the 6 percent average tourmaline in the heavy-mineral suite of the Schuylkill River which drains a relatively dense igneous rock source area; this same mineral comprises 4 percent of the Coastal Plain and 2 percent of other Piedmont heavy mineral fractions.

e. Staurolite tends to increase from 3 to 4 percent in a seaward direction from local source-rich Coastal Plain sediments. This mineral fluctuates most in the source region. Staurolite, for example, is especially abundant in the Crosswich Creek (37 percent) which probably drains the Red Bank Formation rich in this mineral. Staurolite is less abundant farther south in the Coastal Plain streams possibly being diluted by Pleistocene "blanket" deposits which become thicker and increasingly more abundant toward the embayed portion of the estuary.

f. Sillimanite is one of the more consistent heavy minerals in the river estuary with averages ranging between 7 and 11 percent (see Table 2). The sillimanite increases from 7 to 8 percent in the seaward direction with the increase being a result of the Pleistocene sands increasing toward the bay.

g. Epidote decreases from 10 to 2 percent in a seaward direction. Except for local contributions from Schuylkill River, this mineral is impoverished in other sources.

h. Kyanite increases from 1 to 3 percent in a seaward direction with the largest input from the Schuylkill River.

In the foregoing analysis of the change in the heavy-mineral suite between the head of the estuary to the embayed portion of the estuary at Ship John Light, it is apparent that the fluvial Piedmont source is predominant. The major sediment source from Piedmont Rivers dictates the heavy-mineral suite which is characterized by hornblende and garnet. Thus, the Delaware River heavy-mineral province is described for continuity with other heavy mineral provinces as a garnet-hornblende heavy-mineral suite from a fluvial Piedmont source.

Heavy Mineral Analysis of Delaware Bay Sediments

Introduction

Heavy mineral analysis of the sand fraction from 44 bottom sediment samples in Delaware Bay and 32 beach samples around the bay area reveals a pattern of mixed fluvial Piedmont and Coastal Plain heavy mineral suite which is characterized by a high sillimanite fraction. Covering approximately 90 percent of the Delaware Bay area, this heavy-mineral province characterizes the bay except (a) in the landward portion of the bay where the heavy-mineral suite is typical fluvial Piedmont and (b) toward the lower eastern and lower central portions of the bay area in the vicinity of the capes where a sillimanite impoverished heavy-mineral suite intrudes into the bay.

The concentration of heavy minerals (in the sand fraction between 62 and 420 micron size) in the bottom sediment samples of Delaware Bay ranges from trace amounts to 18 percent with an average of approximately three percent. A graphic display of the heavy mineral concentration in the sand fraction for beach and bottom profile samples is shown in Figure 12. The average concentration of the heavy minerals is greater on the Delaware side of the bay which averages four percent for bottom samples tested and includes the two anomalies of 18 percent heavy minerals near Woodland Beach and eight percent heavy minerals off Bowers Beach, Delaware. The transparent fraction of the heavy minerals ranges widely between 29 and 97 percent with a general average approximating 68 percent; mica comprises but a few percent of the heavy mineral fraction. The predominant opaque minerals are magnetite and ilmenite with minor amounts of hematite, leucoxene, and others. The transparent heavy mineral species for the Delaware Bay bottom samples are summarized in Table 2 and are listed for individual locations in Appendix A. Figure 13 is a graphic plot of the heavy minerals for the bay area and tributary rivers to the bay. Some of the more diagnostic minerals will be treated in detail in the following paragraphs.

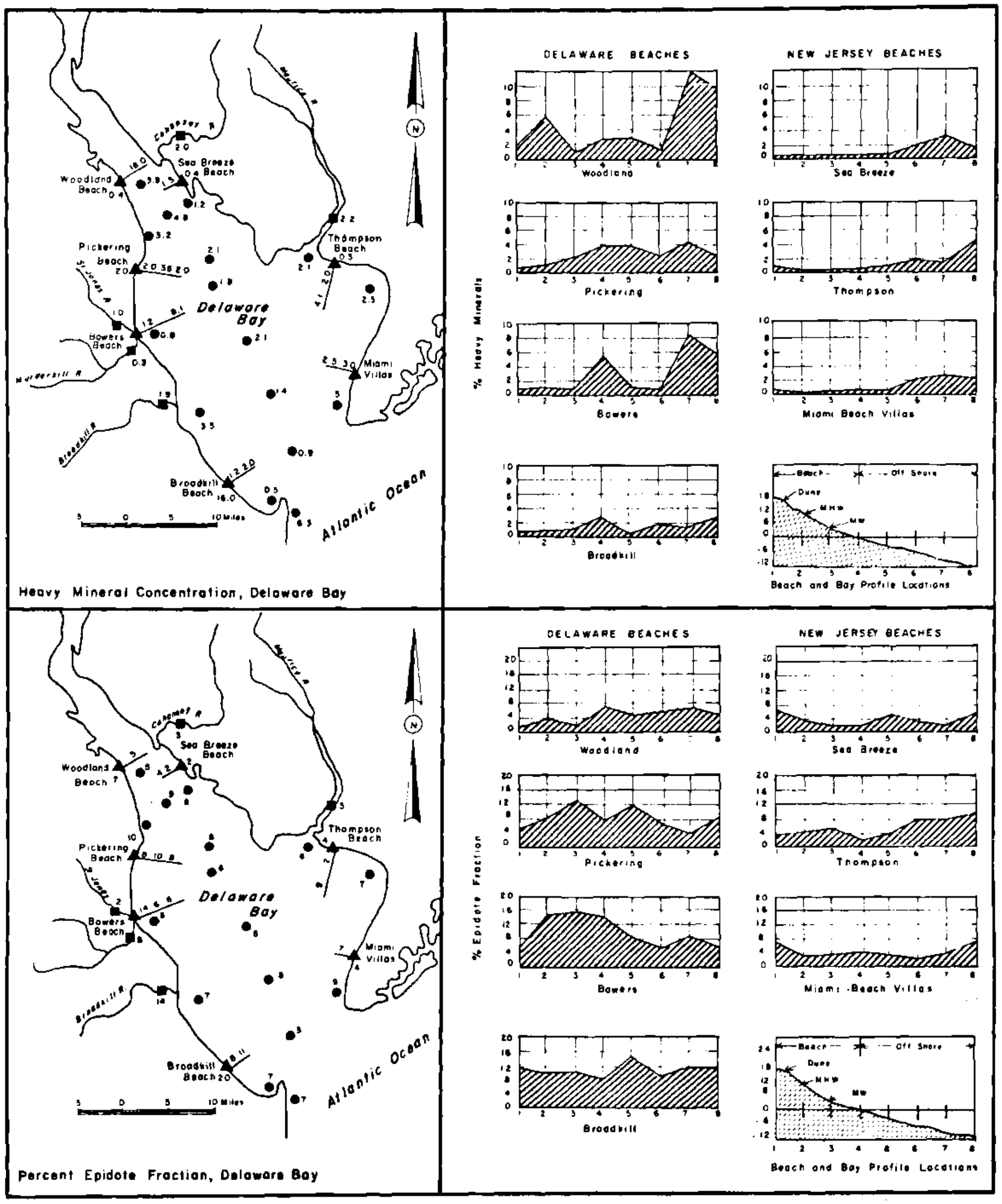


Figure 12. Percent Heavy Mineral Concentration and Percent Epidote in Transparent Heavy-Mineral Sand Fraction from Sediments of Delaware Bay

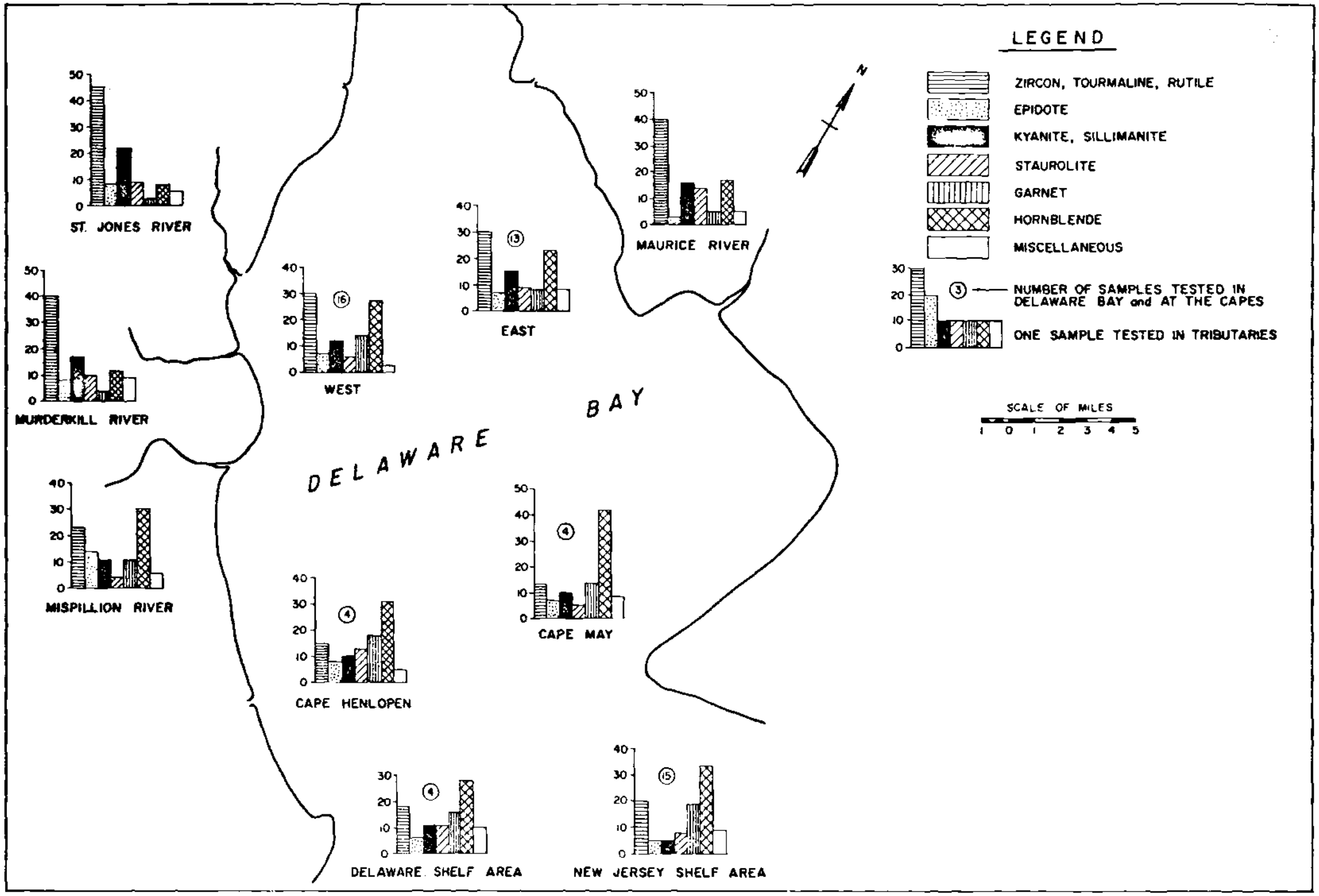


Figure 13. Composition of Transparent Heavy-Mineral Fraction of Delaware Bay and Vicinity

Hornblende and Garnet

Generally high values of both hornblende and garnet prevail in the heavy-minerals suite in the upper bay area with increasing dilution toward the bay beaches. Figure 14 depicts these percentages for sample locations; from the figure it is apparent that values similar to the fluvial Piedmont source from the river estuary prevail in the upper west-central portion of the bay with values of hornblende generally greater than 40 percent of the heavy mineral fraction. Toward the bay margins and the central portion of the bay, hornblende values range between 4 and 40 percent and it is probable that mixing of both Pre-Pleistocene Coastal Plain sediments impoverished in hornblende and the Pleistocene sediment "blanket" deposits rich in hornblende influences these values. The Pleistocene sands in the formations rimming the bay area average 14.2 percent amphibole (predominantly hornblende) in the 75 Pleistocene sediment samples reported by Jordan (1964) and 8 percent for the 25 samples examined from the Pleistocene sediments by Groot (1955); older Coastal Plain formations vary from trace amounts to a few percent (see Figure 6). Erosion of the beaches around the bay and sediment discharge from tributary streams (estimated at 89 tons of heavy minerals annually) and the mixing conditions by waves and currents as cited previously would appear responsible for the hornblende distribution as shown in Figure 14. Toward the lower eastern bay area hornblende values locally in excess of 50 percent are attributed to the high hornblende content of the New Jersey shelf sands which are projected into the lower bay area around Cape May; McMaster (1954) reports an average of 35 percent hornblende in these sands (see

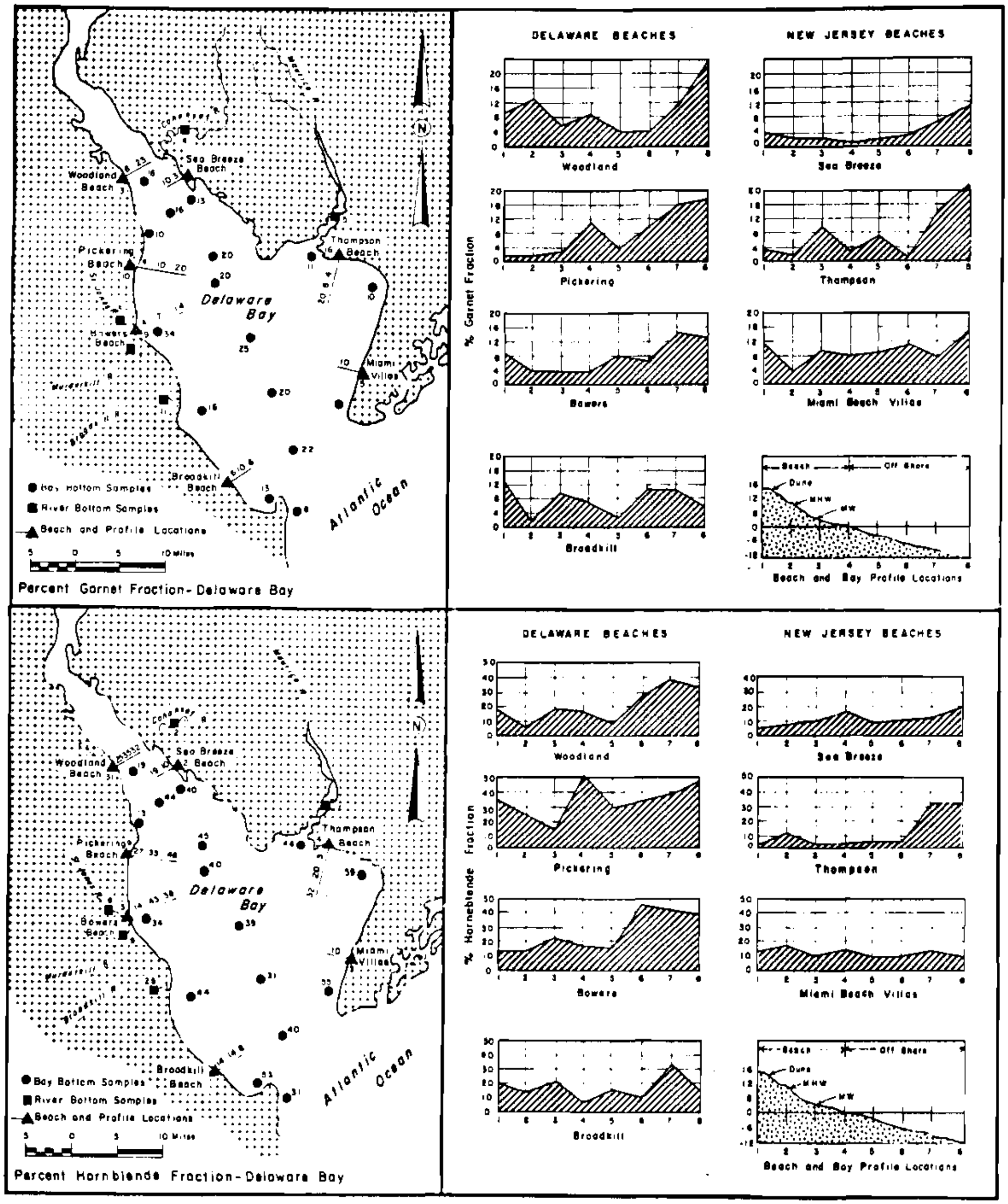


Figure 14. Percent of Hornblende and Garnet in Transparent Heavy-Mineral Suite of Sand Fraction from Bottom and Beach Samples of Delaware Bay

Table 3). The high hornblende values in the bay sediments eliminate the impoverished Coastal Plain formations older than Pleistocene as a source of the sediments.

Garnet values in the upper part of the bay area tend to parallel the trend of hornblende distribution with higher values (20 percent) in a projection of the fluvial Piedmont source heavy minerals into the bay but generally diminishing to about half this amount around the margins of the bay. Both Jordan (1964) and Groot (1955) report an average of two percent garnet in the Pleistocene Formations of the Delaware; unlike the hornblende, however, garnet has a fair representation in the older Cretaceous Coastal Plain Formations where averages between 10 and 20 percent of the transparent heavy mineral fraction occur in the Manasguan, Vincetown, Mount Laurel, and Merchantville Formations (see Figure 6). The generally high values of garnet, ranging between 20 and 25 percent of the heavy mineral fraction toward the central portion of the bay, may be related to the factors contributing to the "lag" deposits previously cited. Coastal sands and glacially derived sands off the New Jersey coast average 16 percent garnet (McMaster, 1954) while garnet in the eastern bay area and margins averages 14 percent. Such similarity in garnet population would appear to support the view that shelf sediment is transported into the bay in this general area.

Zircon, Rutile, and Tourmaline

Zircon, rutile, and tourmaline constitute the most stable heavy mineral species and occur in greatest abundance in older Coastal Plain sediments. Considerable variability has been reported by different investigators for zircon in the Coastal Plain formations with Pleistocene sands averages between 22 percent (Groot, 1955) and 34 percent (Jordan, 1964) and older sediment averaging even higher values. Within the bay area, zircon high values (20 percent) occur around the rim of the bay with but half this amount in the central bay area (see Figure 15). Zircon in the Mantua and Rancocas Creek sediment averages 33 and 28 percent of the heavy mineral fraction reflecting rich source areas in the Coastal Plain sediments drained by these streams.

Rutile, like zircon, is one of the most resistant heavy minerals, and its relative distribution pattern is similar to zircon. Highest rutile concentrations occur in Coastal Plain sediments and streams draining the Coastal Plain (see Table 2); rutile ranges up to six and seven percent, respectively, in Mantua and Rancocas Creeks which also are the sites of highest zircon concentrations in the Coastal Plain sediments. Within the bay area, rutile averages two percent of the heavy mineral fraction with greater occurrence around the margins of the bay area. Rutile, however, is relatively impoverished in the glacially derived shelf sands off the New Jersey coast; McMaster (1954) reports less than one percent rutile in the transparent heavy mineral suite of these sands.

Tourmaline is also one of the most resistant heavy minerals, but unlike zircon and rutile, it is less abundant in Delaware Bay than in the coastal or continental shelf areas. Tourmaline in the bay area averages four percent of the heavy mineral fraction with greatest occurrence around the margin of the bay where values of seven and eight percent are common as shown in Figure 15. Since tourmaline averages five percent in Pleistocene sands and nearly double this amount in older Coastal Plain sediment

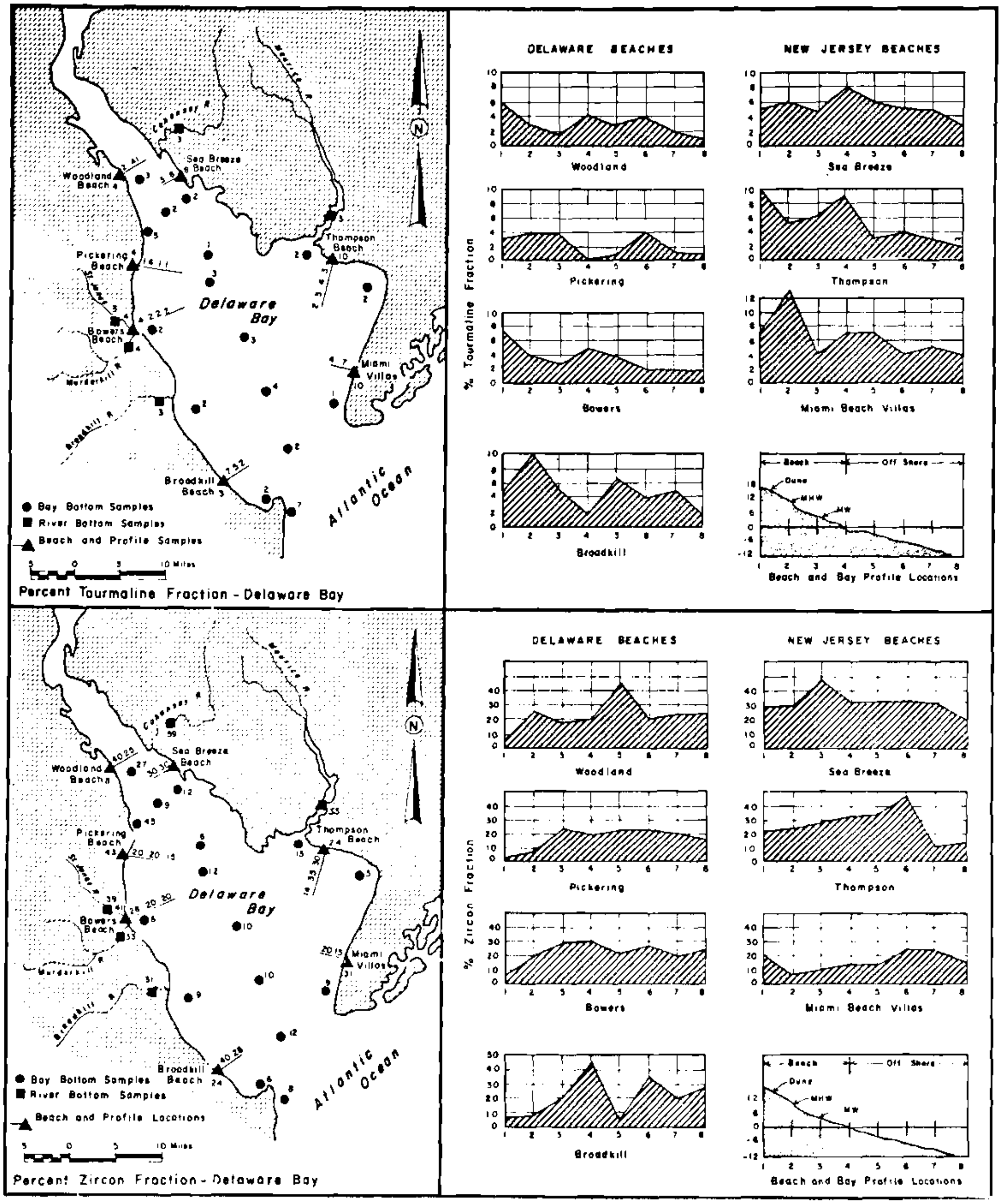


Figure 15. Percent Zircon and Tourmaline in Transparent Heavy-Mineral Suite of Sand Fraction from Bottom and Beach Samples of Delaware Bay

(see Table 2), it would appear that the higher values could possibly reflect erosion of older Coastal Plain formation source areas while in the lower bay area this could reflect the influence of shelf derived sands.

Staurolite, Kyanite, and Sillimanite

Staurolite, kyanite, and sillimanite are varieties of medium and high rank metamorphic minerals but staurolite differs considerably in its distribution pattern from sillimanite and kyanite. Staurolite has an abundant source in Cretaceous sediments whereas sillimanite has greatest population in the Pleistocene sediments; kyanite is always subordinate to sillimanite with a trend similar to sillimanite. Sillimanite averages 12.7 percent and staurolite averages 4.4 percent of the 75 Pleistocene samples reported by Jordan (1964) and the typical Delaware Bay heavy mineral suites are generally of this order of magnitude except along the margins. Staurolite attains highest values off Sea Breeze Beach, New Jersey (25 percent) as a result of eroding Cretaceous Formations (see Figure 16). Another staurolite high (20 percent) occurs in the lower eastern bay area and this is probably related to transport from the glacially derived shelf sediments from the New Jersey Coast; as shown in Table 3, McMaster (1954) reports an average of 13 percent staurolite from this source area. The major portion of the bay area reflects generally low staurolite values and is consistent with the concept of mixing of predominantly Pleistocene Coastal Plain sediment and fluvial Piedmont source sediment; both these sources average four percent staurolite.

Sillimanite averages in the bay area range between 11 and 15 percent except for the lower east bay area where averages are about half

Table 3. Heavy Mineral Distribution in the Vicinity of the Capes and Continental Shelf off Delaware Bay

Heavy Mineral Species	UPPER BAY Delaware West Side	 New Jersey East Side	VICINITY OF CAPES Delaware Bay West Side	 Delaware Bay East Side	 Strom S.W. Del. Bay	CONTINENTAL SHELF New Jersey Coast	 Delaware Coast	 McMaster N.J.Coast	 Shepard & Cohee N.J. Coast	 Alexander Md. Coast
					% Heavy Minerals in Sand Fraction - Range and Average					
	Tr - 18.0 4.0	1 - 6.0 3.0	0.5 - 3.5 1.5	0.8 - 5.0 2.0	-- --	0.0 - 8.1 2.4	1.2 - 1.7 1.6	-- --	-- --	-- --
					% Mineral Species in Transparent Heavy-Mineral Fraction - Range and Average					
Hornblende	8 - 46 28	5 - 59 23	31 - 53 42	13 - 55 31	19 - 49 35	21 - 55 34	27 - 30 28	35	Abt.	Abt.
Staurolite	Tr - 21 6	3 - 26 9	Tr - 12 5	2 - 23 13	1 - 16 6	3 - 18 8	6 - 10 9	13	High	High
Garnet	3 - 34 14	2 - 20 8	6 - 22 14	6 - 24 18	2 - 7 4	6 - 27 14	16 - 19 18	16	High	Higher
Zircon	6 - 50 25	5 - 48 23	6 - 12 9	8 - 15 11	1 - 9 4	9 - 25 15	14 - 15 15	5	Low	Low
Epidote	5 - 14 7	1 - 20 7	5 - 7 7	6 - 9 8	1 - 10 6	3 - 7 5	5 - 6 5	4	Low	Low
Tourmaline	1 - 5 3	1 - 7 4	2 - 7 3	1 - 5 3	4 - 9 7	2 - 5 3	2 - 5 4	5	Abt.	Abt.
Sillimanite	3 - 34 11	5 - 20 13	5 - 30 11	4 - 8 6	6 - 30 15	2 - 7 3	2 - 13 10	3	Low	Higher
Kyanite	Tr - 3 1	1 - 4 2	Tr - 5 2	1 - 4 3	2 - 16 9	1 - 6 2	2 - 3 3	2	Low	Higher
Rutile	1 - 4 2	1 - 6 3	Tr - 1 1	Tr - 2 1	2 - 7 4	1 - 4 2	2 - 3 2	1	Low	Low
No. Samples	16	13	10	4	6	15	5	-	-	-

NOTES:
1. West side bay (vicinity of capes) includes field samples B-8, B-9, B-12, B-13 and East side of bay (vicinity of capes) includes field samples B-1, B-10, B-11, and B-14.
2. Southwest side of bay as reported by Strom (1972). The heavy minerals were recomputed to nonopaque fraction minus micaceous minerals for similar comparison. These averages are included with those of this study for west side of bay in vicinity of the capes.
3. New Jersey coastal sands based on averaged samples of McMaster and Light as reported by Hubert and Neal (1967).
4. Relative abundance of minerals based on Continental shelf studies as reported by Cohee and Shepard (1936) and Alexander (1934).
5. Samples from Continental shelf received from Coastal Engineering Research Center as part of offshore sand sampling program.

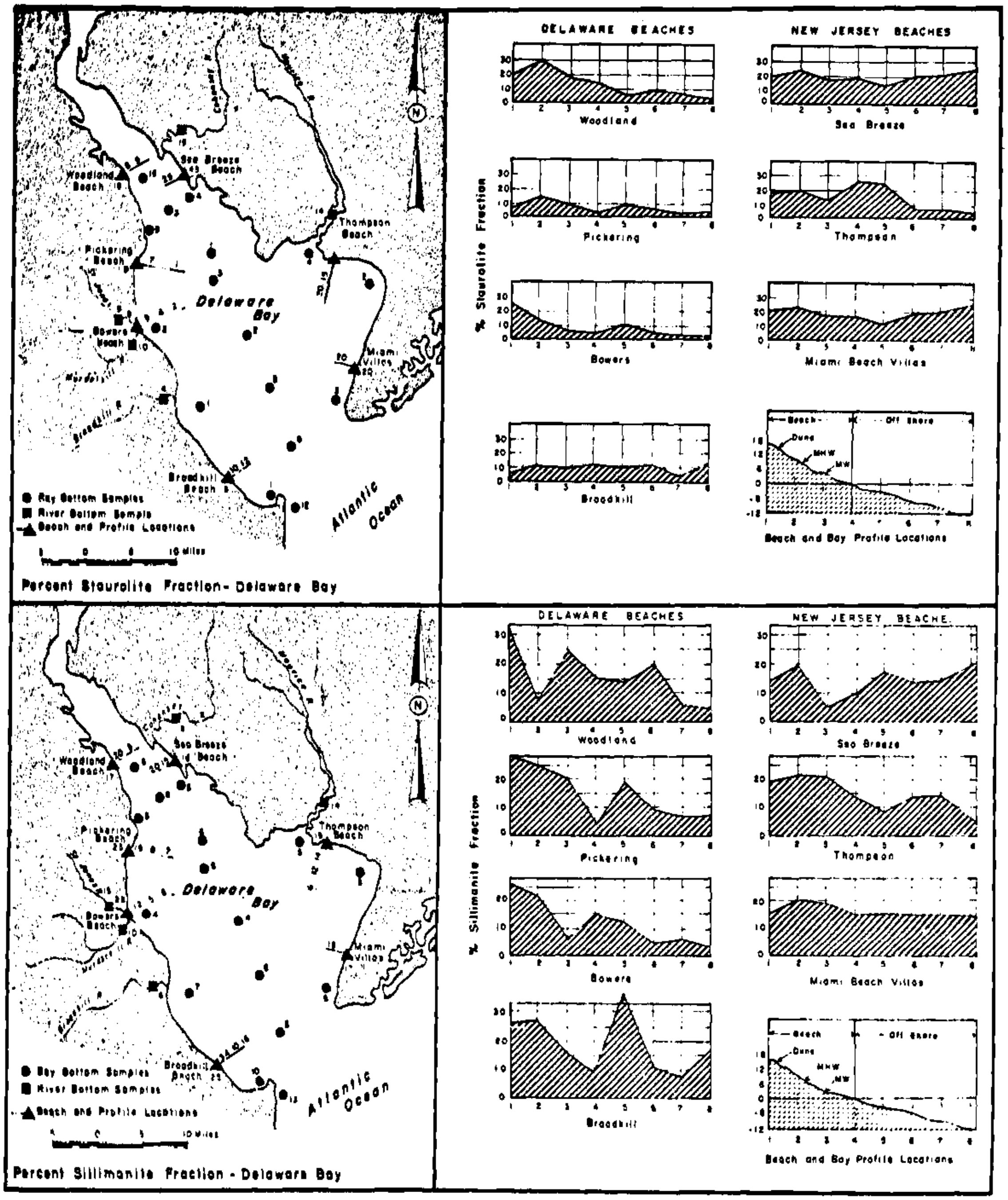


Figure 16. Percent Sillimanite and Staurolite in Transparent Heavy-Mineral Suite of Sand Fraction from Bottom and Beach Samples of Delaware Bay

this much (see Table 3). Lowest sillimanite occurrence found in this investigation was from the shelf area off the New Jersey Coast (three percent) which is also in excellent agreement with the more intensive study of McMaster (1954) for the New Jersey coastal area (see Table 3). Investigation of the southwest corner of Delaware Bay by Strom (1972), provides corroborative evidence of the high sillimanite values (15 percent) in this portion of the bay (see Table 3). Sillimanite along the Delaware coast averages 10 percent and this stands in sharp contrast to the impoverished sillimanite content of the heavy mineral suite of the New Jersey shelf area (see Table 3).

In general, high sillimanite averages and a "full" heavy-mineral suite characterize the "Delaware Bay" heavy mineral province.

Epidote and Pyroxenes

Epidote and pyroxene (augite, hypersthene, and diopside) occur in the Delaware estuary sands but are more variable in distribution than the other heavy minerals. Epidote in Pleistocene formation averages 17.2 percent (Jordan, 1964), seven percent in the bay area (Table 2), four percent in the glacially derived sediment of the shelf (Table 3) and four percent in the Piedmont dominated upper estuary source. Thus, the average bay sediment appears to reflect mixing of appreciable Coastal Plain Pleistocene sands for the seven percent average found in Delaware Bay.

Pyroxenes, as orthopyroxene (hypersthene) and clinopyroxene (augite and diopside), comprise from one to four percent of the bay sediment with highest values in the lower eastern portion of the bay (see Table 4 of Appendix A). Highest source areas of pyroxene, especially hypersthene, is from Piedmont formations at discharge points south of Philadelphia; the nine percent total pyroxenes occurring here are more local with dispersal to a few percent within several miles in a seaward direction (see Appendix A). Hubert and Neal (1967) report eight percent pyroxene from investigations off the New Jersey coastal and shelf areas and this may account for the highest pyroxene values in the lower eastern portion of Delaware Bay. Coastal Plain formations average up to two percent pyroxene in younger Pleistocene sediments (Jordan, 1964) but are impoverished in older Coastal Plain formations. Thus, the low pyroxene values for the "Delaware Bay" heavy mineral province are consistent with source areas delineated by other heavy minerals.

Chloritoid ranges from trace amounts to one percent of the bay sands. Both tremelite and actinolite are present throughout the bay in amounts ranging from one to four percent but show no distinct pattern.

Heavy Mineral Provinces of Delaware Bay

The foregoing description of the heavy mineral distribution in the bay bottom sediments clearly defines the following heavy mineral provinces:

a. The Delaware River estuary between Trenton and the bay contains a fluvial Piedmont dominated heavy mineral suite rich in hornblende and garnet. Toward the bay, the Coastal Plain source sediments become increasingly greater.

b. The upper and central bay areas are characterized by a "full" heavy-mineral suite, i.e., heavy-minerals of all stability ranges and abundant sillimanite. Sillimanite is in similar proportions in this heavy-mineral suite of mixed Coastal Plain and Piedmont source materials and thus maintains a similar value while less resistant Piedmont minerals (hornblende and garnet) are somewhat reduced in value as are likewise the stable minerals (zircon, rutile, and tourmaline of the Coastal Plain formations. The "Delaware Bay" heavy mineral province extends the full length of the western bay area (see Figure 17). Based on hornblende reduction, it is estimated that 70 percent of Delaware Bay is characterized by this sillimanite-rich heavy-mineral suite. A recent investigation of seven bottom samples in the southwest corner of Delaware Bay for heavy minerals by Strom (1972) provides corroborative evidence for including this southwestern bay area in the "Delaware Bay" heavy mineral province (see Table 3).

c. The lower east and central bay areas contain a heavy-mineral suite of mixed "Delaware Bay" and glacially-derived continental shelf sands. Sillimanite in this mixed suite ranges from four to eight percent and pyroxene attains highest values in the bay area. Distribution of the sediment drift, reflected by the heavy minerals, correlates with hydrodynamic investigations which will be described in the following sections.

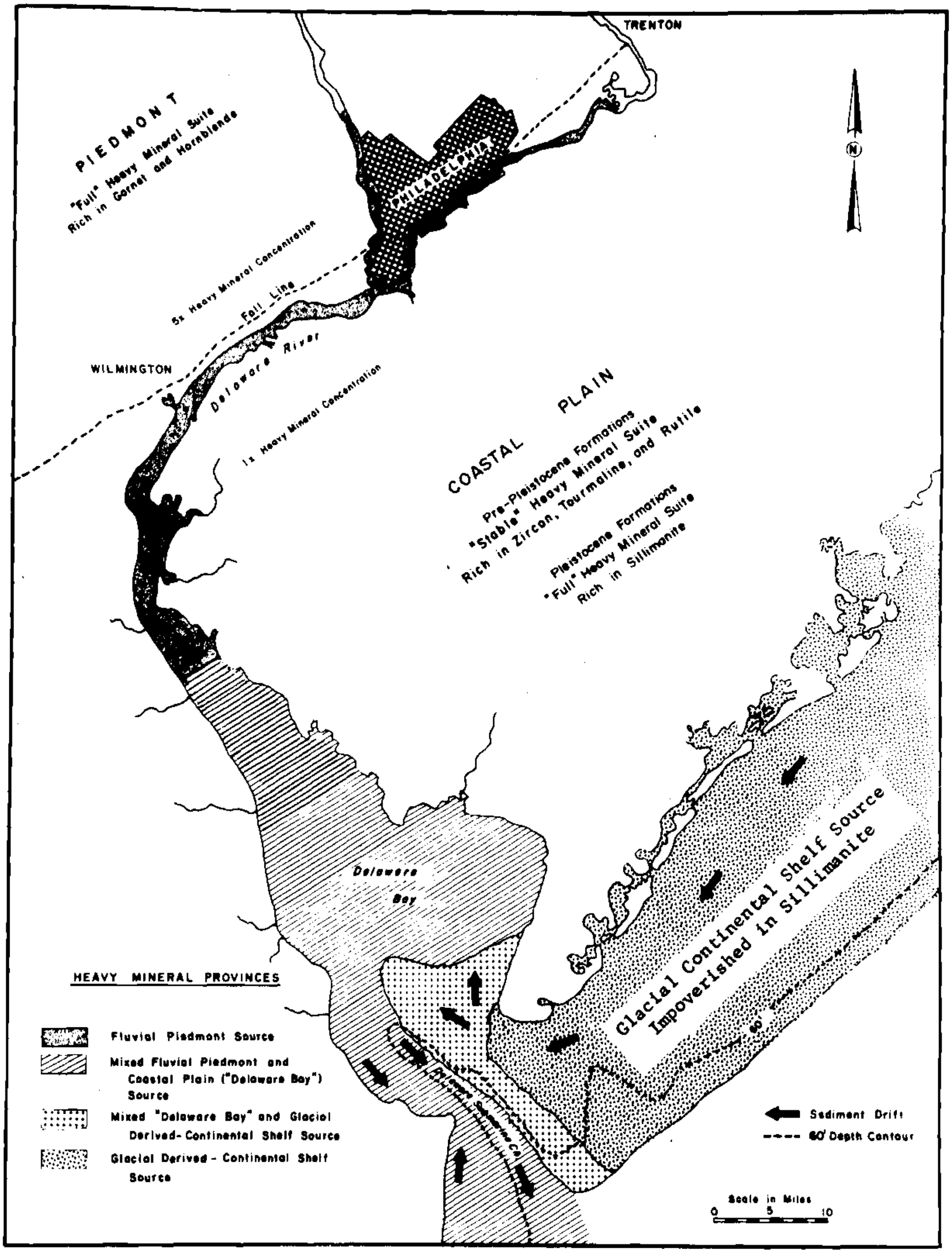


Figure 17. Sediment Source and Dispersal Direction of Sand Size Sediment of Delaware River Estuary and Bay-Based on Heavy Mineral Assemblages

CHAPTER VI

HEAVY MINERAL DISTRIBUTION IN THE VICINITY OF THE CAPES

General Considerations

Several investigations of the hydrodynamics and sediment of the New Jersey and Delaware coastal areas in the vicinity of the Delaware Bay capes have been conducted by the U. S. Army, Corps of Engineers (1972, 1968, 1963, 1959, 1946), Bumpus (1965), Meade (1969), Moody (1964), Kraft (1971), Fairchild (1966), and others. The sediments off the New Jersey coast are coarser grained than those off the Delaware coast and it is apparent that mixing of sediment does not occur between the capes; current studies and diagnostic heavy minerals will be shown to support this view. In the vicinity of the capes, strong erosion is in progress with littoral currents around the capes into the bay from the seaward direction.

Bottom sediment samples for heavy minerals in this phase of the investigation were provided by the Coastal Engineering Research Center and the University of Delaware; two samples were provided in the vicinity of the capes by Philadelphia District.

New Jersey Coast in the Vicinity of Cape May

U. S. Corps of Engineers (1972) records reveal that erosion has been prevalent from Cape May point to three miles north along the New Jersey coast since earliest survey records to 1842. Waves as high as

15 feet have been reported in the breaker zone near the capes (U. S. Army, Corps of Engineers, 1959). Based on hindcasting methods from wind roses compiled over a period of years (see Figure 18) waves in excess of six feet in height occur off the Delaware Bay entrance about 15 percent of the time. The predominant littoral current produced by the refracted waves is in a southerly direction from a point about 60 miles north of Cape May toward the bay entrance. Cape May is an eroding Pleistocene ridge and the south-westerly longshore drift has been estimated by Fairchild (1966) at 20,000 cubic yards per year; some of this sediment builds up the extensive shoals and banks of coarse sediments off Cape May point.

An investigation of the net movement of bottom water on the continental shelf area south of Cape Cod by Bumpus (1965) using records of sea-bed drifters released at sea and eventually recovered by fishermen and beachcombers indicated movement of bottom currents around Cape May into the bay (see Figure 19). Sediment drift also follows this general directional movement as will be shown by diagnostic heavy minerals.

Delaware Coast in the Vicinity of Cape Henlopen

Records of the the U. S. Army, Corps of Engineers (1968) reveal that, since 1843, strong erosion at a rate of 7 to 10 feet per year has occurred along the Delaware coast for the two miles of beach extending southward from the tip of Cape Henlopen. The shoreline from Cape Henlopen to Rehoboth Beach has experienced a continual landward recession averaging six feet per year while the shoreline from Rehoboth Beach to 1.8 miles above Indian River Inlet has receded four feet per year for most of the same period of time since 1843. The eroding materials have

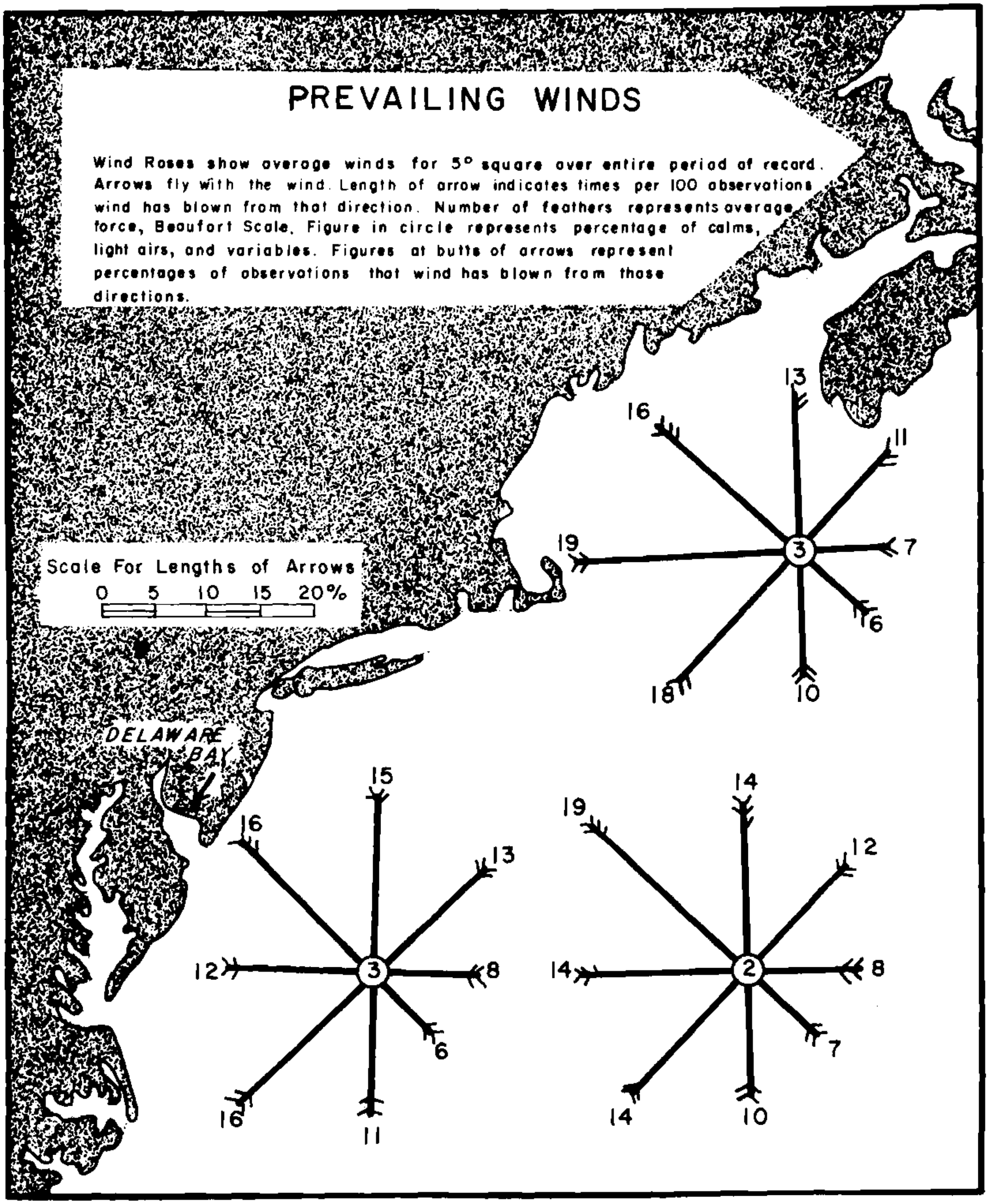


Figure 18. Wind Roses Showing Average Wind Force and Direction for Period of Record

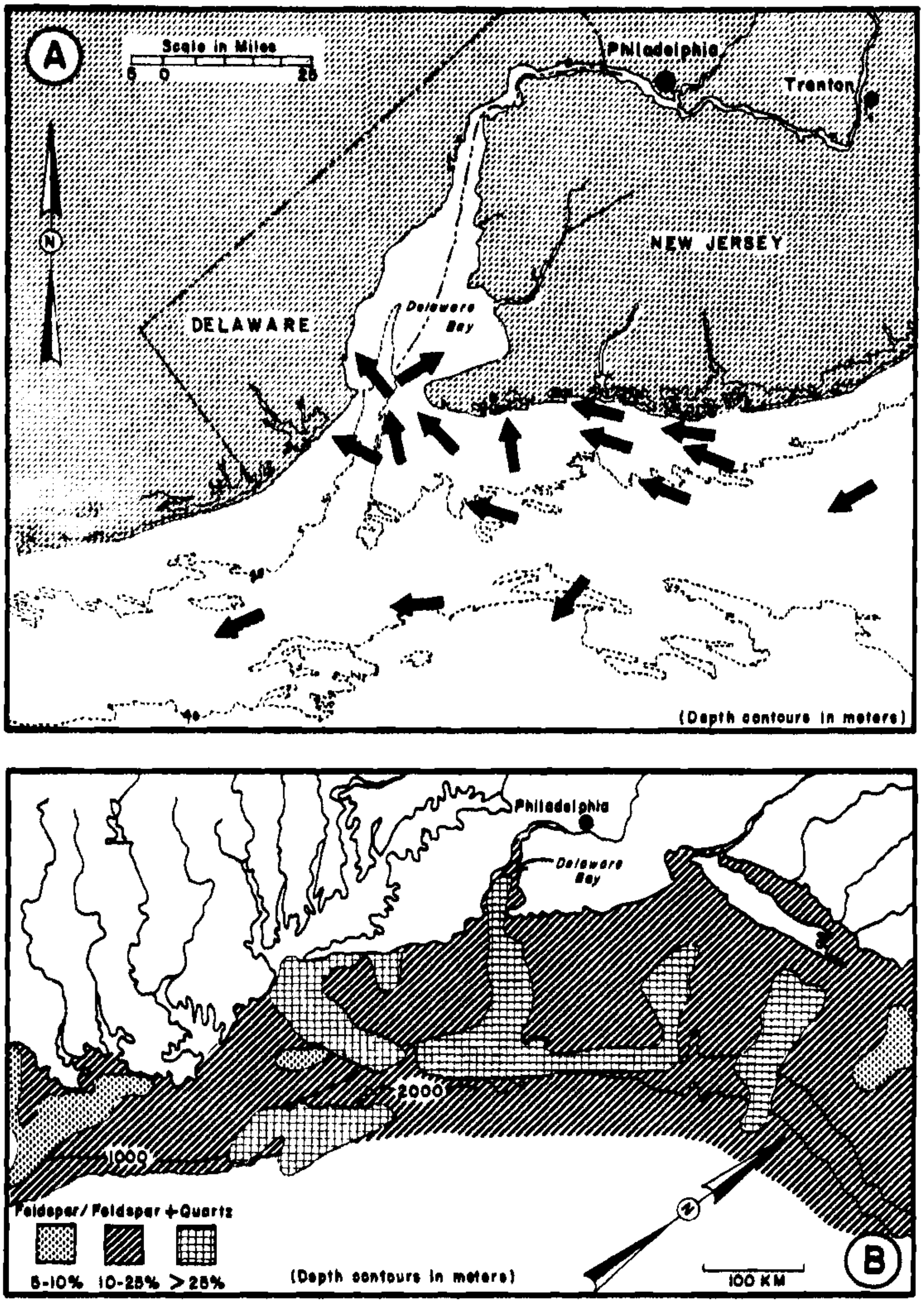


Figure 19. Direction of General Residual Current Along the Bottom on the Continental Shelf (Bumpus, 1964) and the Ratio of Feldspar to Feldspar + Quartz (f/f+q) in the 125 to 250 Micron Fraction of Surface Sediment on the Continental Shelf (Milliman, et al., 1972)

provided sediment to the northerly directed littoral drift along this section of Delaware coast, and the northern tip of Cape Henlopen has been extended bayward approximately 3,850 feet north of its 1843 location. Turner (1968) has estimated the northward longshore transport past Cape Henlopen as 450,000 cubic yards per year.

According to Moody (1964), Cape Henlopen is probably several thousand years old having grown northward from Rehoboth Beach over gently sloping gravel deposits left by the Delaware River during the last sea level recession. Kraft (1971) predicts that Cape Henlopen is slated to become a recurved spit of the type that it was in the prehistoric past; in the process it will join with the southwest corner of Delaware Bay mainland (see Figure 7).

Bathymetry in the Vicinity of the Capes

The submarine topography of the approaches to Delaware Bay is depicted in Figure 20. A ridge and trough topography with northeast or east northeast trend is characteristic. Some of the shoals near Cape May conform to the orientation of the coastline and curves into the mouth of Delaware Bay. Perhaps one of the most striking bottom features is the Delaware submarine channel approximately five miles east of Cape Henlopen; this feature has a narrow channel with depths in excess of 100 feet extending for 50 miles to the southeast across the continental shelf. Kraft (1971) has shown this submarine channel to be the site of ancestoral Delaware Bay approximately 7,000 years before the present (see Figure 21). This feature probably attained its greatest depth during the lower sea level approximately 10,000 years before the present. Sediment distribution

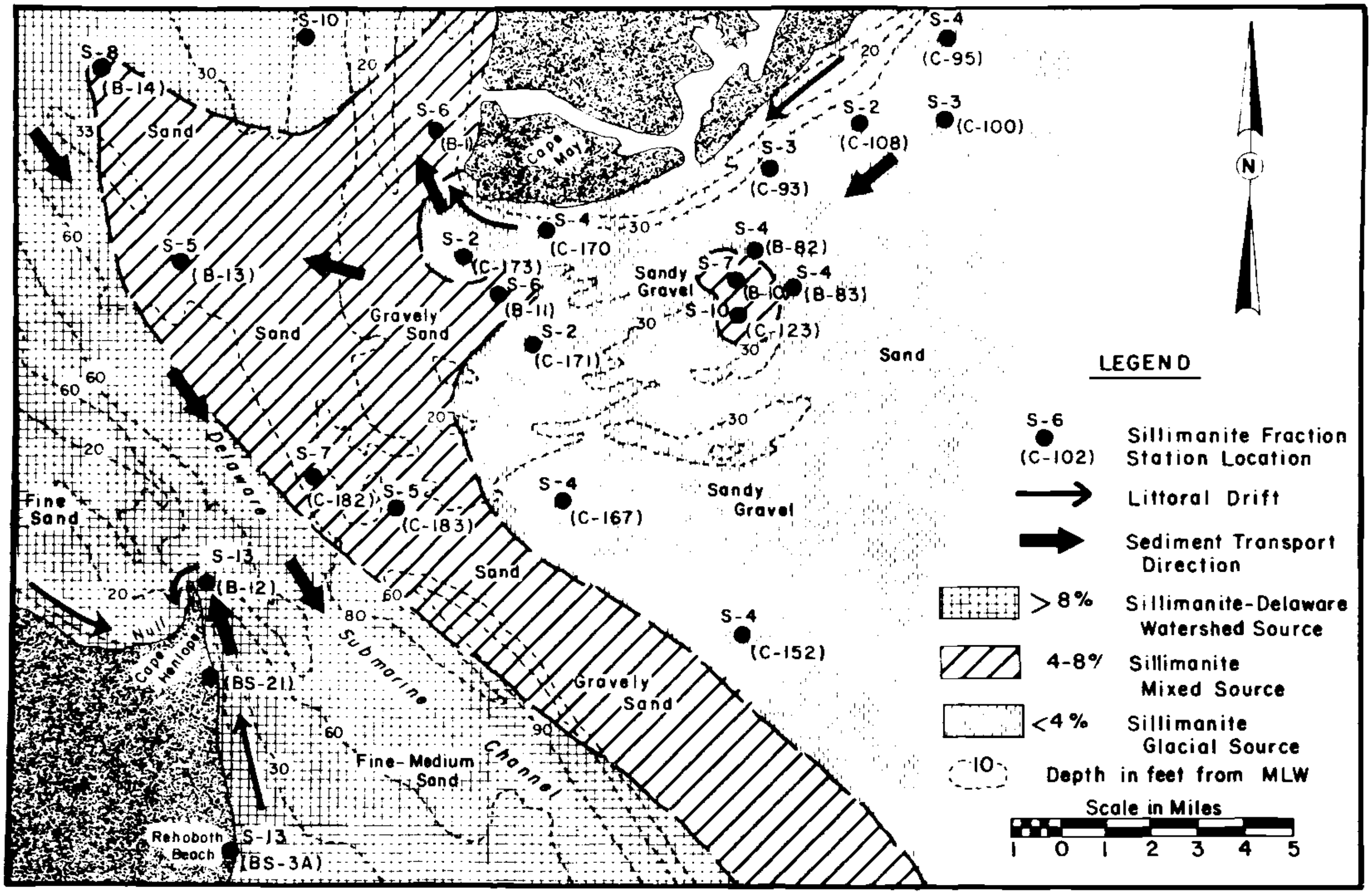


Figure 20. Sediment Drift in the Vicinity of the Delaware Bay Capes Based on Sillimanite Dispersal Patterns. (Generalized sediment occurrence after Moody (1964); littoral currents after Kraft (1971) and Corps of Engineers (1972); bottom currents after C & G chart 1219.)

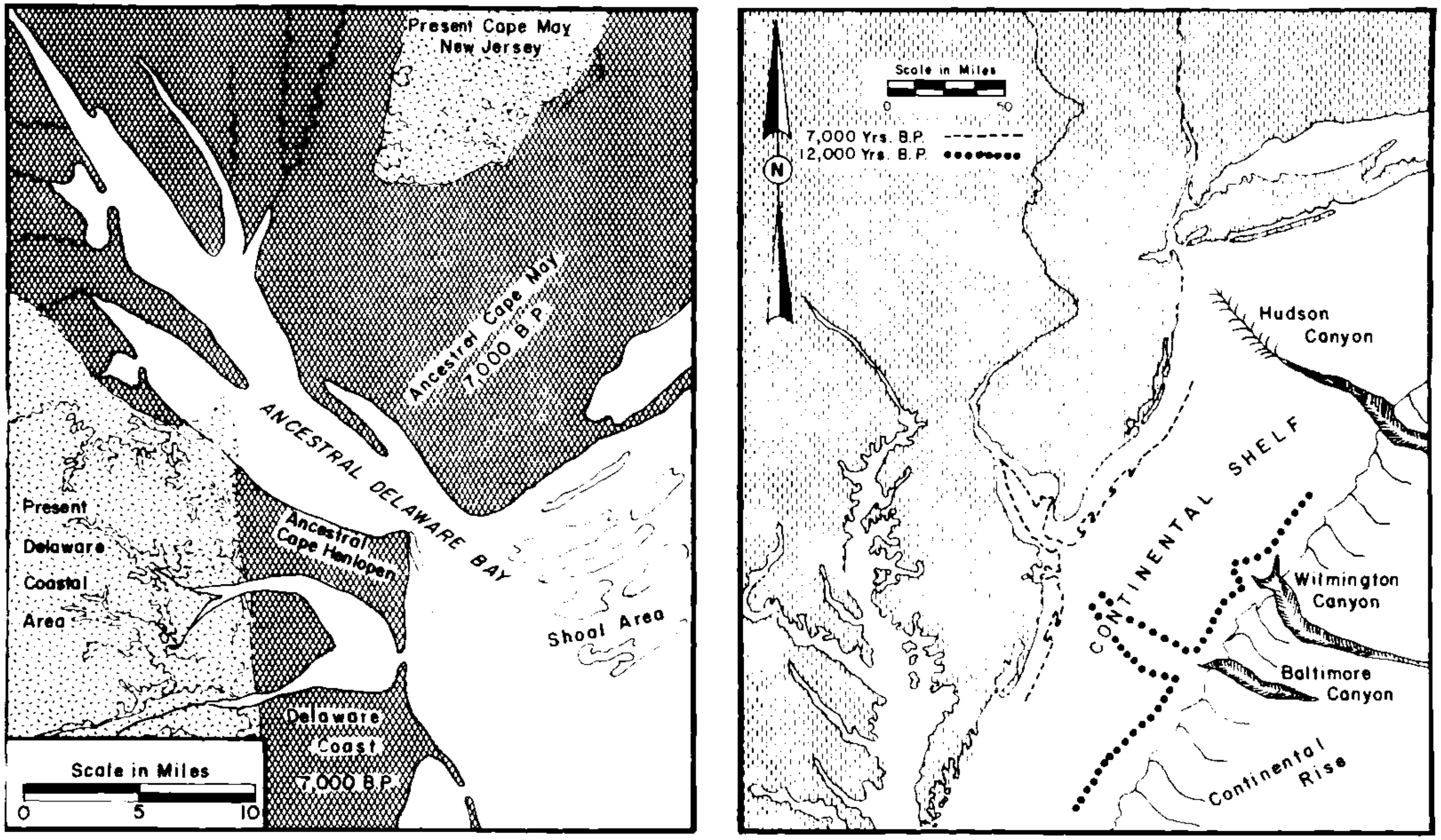


Figure 21. Paleogeography of the Continental Shelf and Coastal Area off Delaware and New Jersey 7,000 and 12,000 Years before the Present. (After Kraft (1971).)

also conforms to this Pleistocene feature as will be shown in a later section of this report.

An important shoal area, Hen and Chicken Shoal, occurs between the submarine channel and the Delaware shoreline (see Figure 7). This shoal extends 12 miles south of Cape Henlopen and terminates six miles offshore. The shoal is 2.5 miles wide at the southern end and tapers to less than 0.2 mile at Cape Henlopen where it has a maximum relief of about 36 feet on its northeast side.

Other submarine features include flat, terrace-like surfaces bordering the Delaware submarine channel and a series of ridges and troughs which project northeastward along the Delaware coast.

Sediment in the Vicinity of the Capes

The sediments in the vicinity of the capes have been described by Moody (1964) and general types are depicted in Figure 20. The terraces east and west of the submarine channel are covered with sand, gravelly sand, and scattered patches of sandy gravel in depressions. Sand and gravelly sand occur in the submarine channel; local sandy gravels are probably fluvial deposits from the Delaware River when sea level was lower. Sandy silt and gravelly sand cover seaward parts of Hen and Chicken Shoal and the bottom sediments between the shoreline and shoal. Texture examination of Cape Henlopen beach materials by U. S. Army, Corps of Engineers (1968) supports the view that little if any material from the New Jersey beaches crosses the Delaware Bay to feed the Delaware beaches. Heavy mineral provinces delineated in this investigation support this view as will be demonstrated later.

Heavy Mineral Distribution in Continental Shelf Sands

Investigations of the heavy minerals of the continental shelf sediments between Nova Scotia and Delaware Bay have been reported by Alexander (1934), Shepard and Cohee (1936), McMaster (1954), Ross (1970), Milliman (1972), Stanley, et al. (1972), Hubert and Neal (1967), and others. Sediments from this source are largely glacially derived and many of the heavy minerals occur in similar proportions as in Delaware Bay; notable differences, however, include impoverishment of sillimanite and the increased amounts of staurolite, garnet, and pyroxene (see Table 3). Sillimanite reported by McMaster (1954) along the New Jersey coast and shelf is consistent in low values with an average of three percent reported. Alexander (1934), in analysis of heavy mineral transects along the continental shelf which were off the northern New Jersey and Maryland coast observed that sillimanite (fibrolite) and kyanite are more abundant in the Maryland sands; this will be shown to be a highly significant observation.

Swift, et al. (1971), discussed the effect of stripped sediment from retreating shore faces on a transgressing sea such as occurred in the late Pleistocene for the Sable Island banks to the north of the Delaware Bay area. Similar effects undoubtedly occur in the vicinity of Delaware Bay on Pleistocene surfaces and this aspect must be considered in evaluations of heavy mineral occurrences of the study area.

Sillimanite Distribution in the Vicinity of the Capes

The sillimanite fraction of heavy minerals in the surface bottom sediment of 23 samples in the vicinity of the capes is depicted in Figure 20. The impoverished sillimanite, ranging from two to four percent off the New Jersey coast to the vicinity of Cape May shoals is in excellent agreement with McMaster (1954). In the shoal areas off Cape May local anomalies of higher sillimanite values occur in a sandy gravel area but sillimanite elsewhere to the vicinity of Cape May does not exceed four percent of the heavy mineral fraction. In the lower eastern bay area and lower central bay area sillimanite values range between four and eight percent and represent a mixed Delaware Bay and glacially derived continental shelf source in a band three to seven miles wide extending in a SE direction. Values of sillimanite in excess of eight percent of the transparent heavy mineral are considered as the "Delaware Bay" heavy-mineral suite (see Figures 17 and 20).

The sillimanite dispersal pattern reflects the residual bottom drift reported by Bumpus (1954) except that sediment drift does not extend across the Delaware submarine channel or between inlets (see Figure 19). The investigation of bottom currents in Delaware Bay by Oostdam (1971), however, is in agreement with sillimanite distributions patterns; as shown in Figure 22, current roses show general parallelism with the Delaware submarine channel. Maximum ebb and flood flow directions depicted in Figure 9 from Coast and Geodetic Survey (1960) data show similar directional patterns. Sillimanite average values of 15 percent reported by Strom (1972) in the lower southwest portion of Delaware Bay are also corroborative evidence that mixing of sediment drift is not between the capes.

The Delaware Bay sediment characterized by the greater than eight

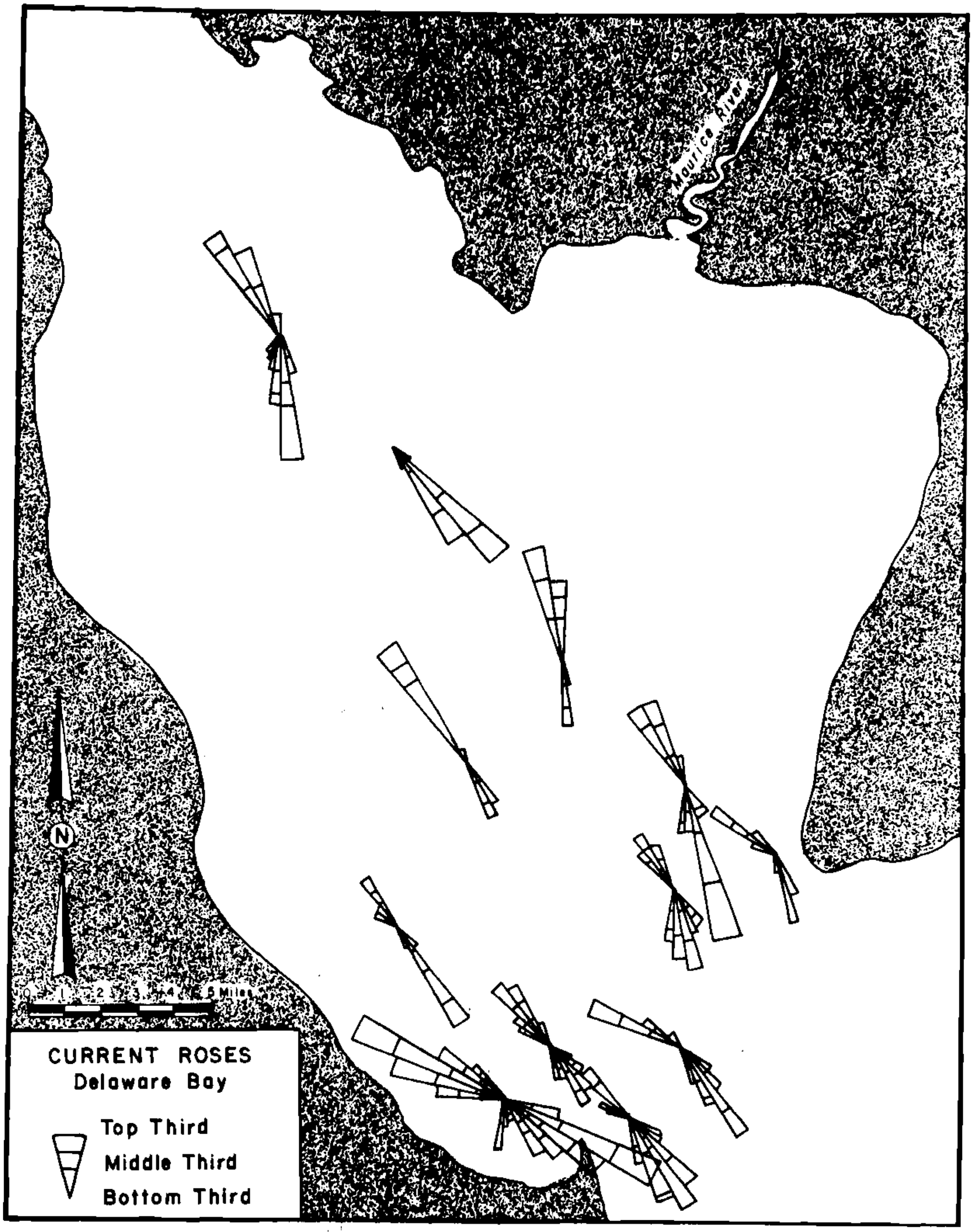


Figure 22. Current Roses of Delaware Bay Showing Directions into Which Currents Are Running for the Top, Middle, and Lower Thirds of the Water Column. (Length of vector gives measure of consistency of current directions. After Oostdam (1971).)

percent sillimanite in the heavy-mineral fraction appears to extend from the bay area along the western side via the Delaware submarine channel, which Kraft (1971) has shown to be the site of ancestoral Delaware Bay (see Figure 21). Coastline hydrodynamics are such along the Delaware coast that littoral currents are transporting sand from Hen and Chicken shoals just south of the bay. A null point or area of non-transport exists on the bay side of the cape and represents the maximum landward projection of sand into the bay from the Delaware coast (see Figure 7).

Sediment Drift Reflected by Sillimanite

The sillimanite distribution pattern reflects sediment drift in compliance with measured hydrodynamic parameters and reflects Pleistocene surfaces as follows:

(a) Sediment transport along the New Jersey coast and shelf area from at least 60 miles north of Cape May is in a southerly direction with some of the sand transported into the lower eastern and central portions of the bay and another component projected to the shoals off Cape May.

(b) Gravelly sands in some of the bathymetry locations off Cape May may reflect relict or palimpset sediment from fluvial Pleistocene surfaces.

(c) Delaware Bay sediments appear to move onto the continental shelf along the western side of the bay via Delaware submarine channel, the site of ancestoral Delaware Bay.

(d) Littoral currents along the northern Delaware coast are moving sediment into the southwestern corner of Delaware Bay from eroding Delaware shoals and beaches.

(e) Sediment differences, including texture and heavy minerals, suggest that there is no direct mixing between the capes.

The net sediment drift from the Delaware River to Delaware Bay is summarized in Figure 17 for evidence existing in heavy mineral assemblages and hydrodynamic factors. The strong fluvial Piedmont dominated source emanating from the river estuary gives way to the sillimanite-rich mixed Coastal Plain and fluvial Piedmont source sediment constituting the major portion of the bay bottom sediments. The bay sediment is projected seaward along Pleistocene carved surfaces to the Continental Shelf. Continental Shelf sand impoverished in sillimanite is projected into the lower eastern and lower central bay areas by littoral currents from the New Jersey coast. Cape Henlopen on the northern Delaware coast is being projected into the bay by sediment drift in a northerly direction along the Delaware coast from a sillimanite-rich heavy mineral source.

Feldspar as Corroborative Evidence of Sediment Drift

Milliman, et al. (1972) show tongues of arkosic sediment stretching across the continental shelf area from eastern Long Island, the Bight of New York, Delaware Bay, and Chesapeake Bay (see Figure 19B); these are thought to be from rivers draining glacier-covered terrain during the last glaciation. The feldspar is expressed as a ratio of feldspar to feldspar plus quartz for sediment in the 125 to 250 micron size. The examination of the feldspar fraction of Delaware Bay and coastal sediments in the vicinity of the capes for the 125 to 177 micron size shows comparable highs and lows (see Figure 23). As shown in Figure 23, the feldspar from the eastern side of Delaware Bay ranges from four to ten percent

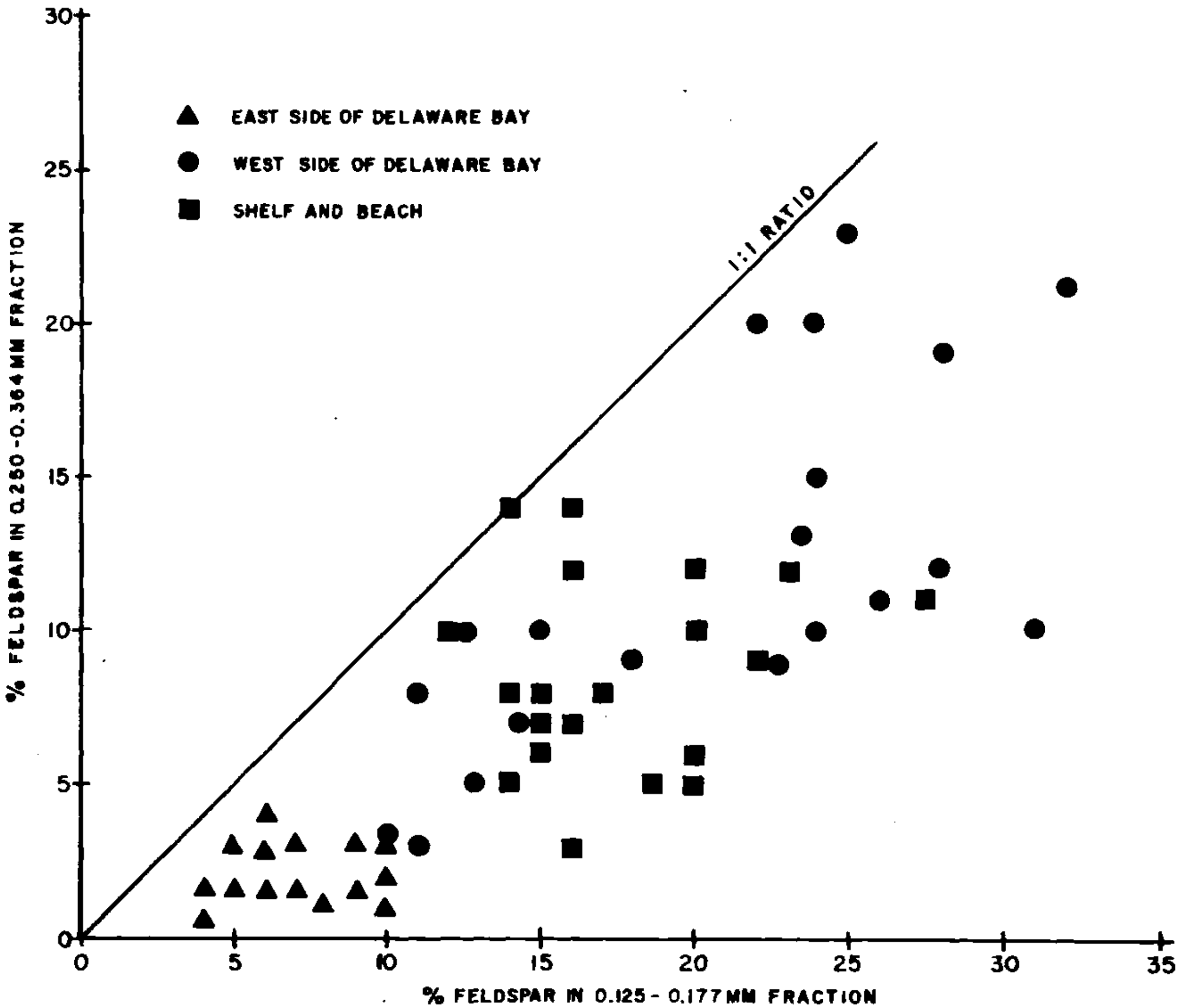


Figure 23. Plot of Feldspar Abundance in Two Size Fractions of Sand from Delaware Bay and Shelf Areas in the Vicinity of the Capes

(this would be slightly higher using the ratio method expressed by Milliman, et al., 1972) and 8 to 28 percent for the western side of Delaware Bay. The coastal sands near the Delaware coast reflect the higher ratios up to 33 percent and the coastal sands toward the New Jersey coast the lower values, thus presenting corroborative evidence that the feldspar is from Pleistocene terraine. Feldspar values of contemporary fluvial Piedmont source sand-size sediment of the river estuary ranges between 2 and 19 percent with a general average of 6 percent. Similar low values exist in tributary streams draining areas virtually free of Pleistocene deposits. Jordan (1964) reports a range of 4 to 37 percent an an average of 18.4 percent feldspar in 75 samples of Pleistocene sands from Delaware; these values would also be somewhat higher if expressed in similar size fractions as Milliman, et al. (1972). Thus, within the Delaware Bay area, the higher feldspar content on the west side of the bay correlates with the "Delaware Bay" heavy mineral province while the eastern portion of the bay reflects (a) older Coastal Plain source formation impoverished in feldspar and (b) influence of sediment transported around Cape May from the New Jersey coastal sands generally low in feldspar.

CHAPTER VII

HEAVY MINERALS OF THE ATLANTIC CONTINENTAL SHELF

General Considerations

The sediments and heavy mineral provinces of the Atlantic Continental Shelf have been described by Milliman, et al. (1972) and Hubert and Neal (1967) and other investigators have described more localized portions of the shelf. According to Milliman, et al. (1972), almost the entire shelf is covered by sand, mostly medium in size, and the silt and clay content rarely exceeds more than one percent. Most of the shelf sediments are shallow water deposits representing accumulations during the last lower stand of sea level; modern sediments are accumulating only in estuaries, such as shown at the mouth of Delaware Bay, and in certain nearshore areas and on the continental slope. Milliman, et al. (1972) have also shown that shelf sediments north of latitude 41 degrees were deposited by Pleistocene glaciers that covered the area; to the south the middle Atlantic shelf sediments consist predominantly of arkosic to subarkosic fluvial sand while the inner shelf off the southeastern United States is covered by suborthoquartzitic fluvial sands derived mostly from Piedmont rivers (see Figure 24).

In the heavy mineral analysis of the continental shelf, Milliman, et al. (1972) cite four transparent heavy mineral species as the most useful in determining the sediment source; they are hornblende, epidote,

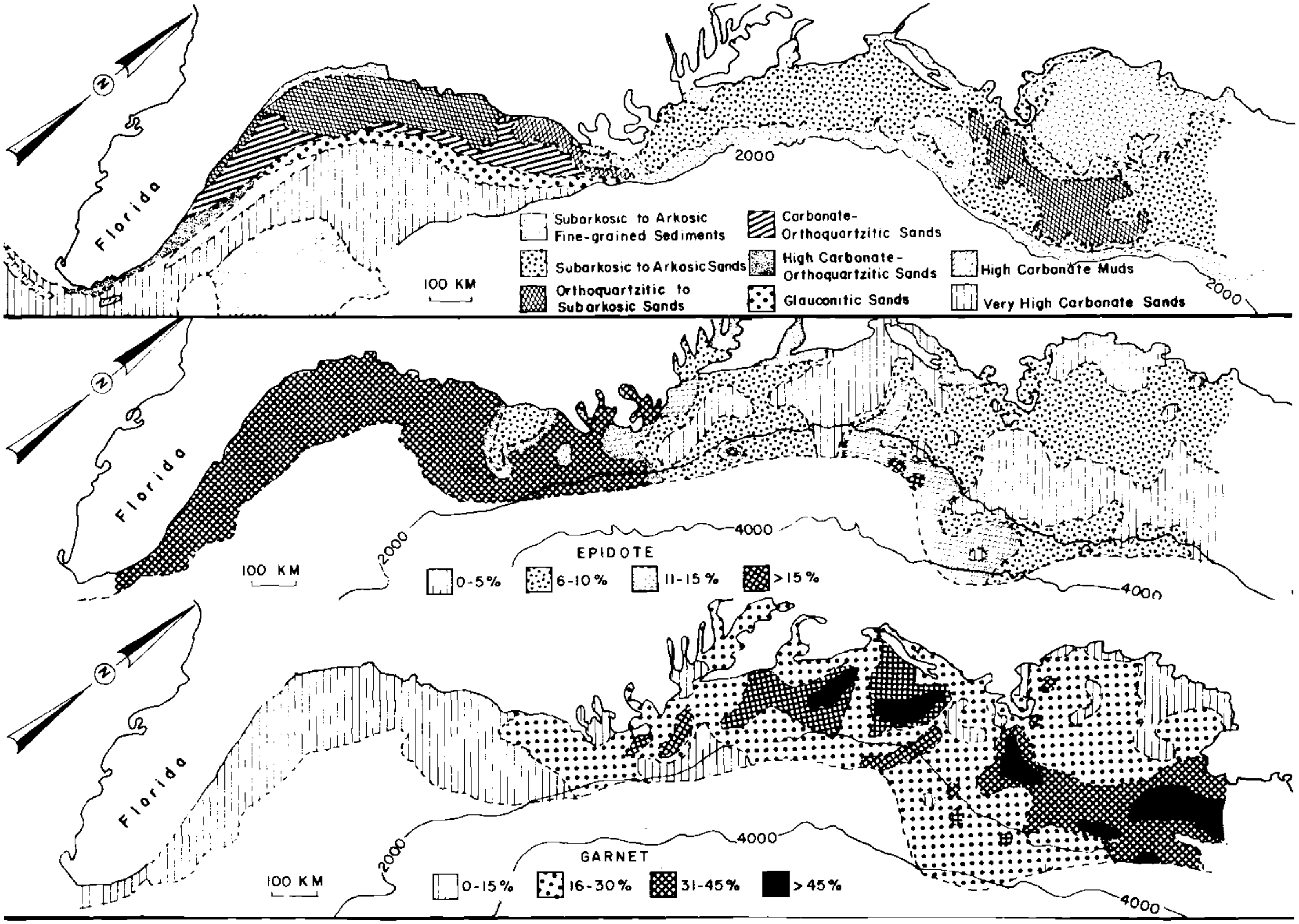


Figure 24. Distribution of Garnet and Epidote within the Heavy Mineral Fraction and Sediment Types on the Atlantic Continental Shelf (After Milliman, et al. (1972))

garnet, and staurolite. As shown in Figure 24, garnets are abundant north of Cape Hatteras, especially off Long Island and on the Georges Bank-Scotian shelf area but they are relatively rare south of Cape Hatteras. Epidote distribution, also depicted in Figure 24, is relatively rare north of Cape Hatteras but fairly common to the south. Hornblende is relatively abundant in nearshore and protected areas and most common between Cape Hatteras to slightly south of Delaware Bay. Staurolite is common north of Long Island but generally low in quantity between Long Island and Cape Hatteras; this mineral increases further south especially off Cape Fear.

While the heavy minerals cited show greatest contrast over the entire Atlantic Continental Shelf, local heavy mineral provinces are characterized by specific species related to source areas or marked differences in energy zones. An example of this has been demonstrated in the case of sillimanite in the vicinity of Delaware estuary.

Heavy Minerals of the Northern and Middle Continental Shelf Areas

The heavy mineral provinces and sub-provinces of the northern Atlantic Continental Shelf have been described by McCarthy (1931), Alexander (1934), Shepard and Cohee (1936), McMaster and Garrison (1966), Hubert and Neal (1967), Ross (1970), Stanley, et al. (1972), and Milliman, et al. (1972). The complex glacial assemblages of the continental shelf off Nova Scotia and New England have been described by Ross (1970) and Stanley, et al. (1972). Ross (1970) has characterized the heavy minerals of the glacial assemblages on the basis of 25 transparent species; hornblende and garnet are relatively abundant but moderate quantities of pyroxene and apatite distinguish it from the provinces south of the Hudson Bay (see Figure 25). As shown in Figure 25, McMaster (1954) also reflects a glacial source along the New Jersey coast characterized by three percent sillimanite, two percent kyanite, and eight percent pyroxene.

As described in previous sections, glacially derived heavy minerals of the New Jersey coast are transported into the eastern portion of Delaware Bay and onto the shoals off Cape May but do not mix across the capes (see Figure 17). Sillimanite is impoverished in the glacial source sands largely in relation to source but also possibly in relation to the higher energy zone off the New Jersey coast. The marked increase of sillimanite in the continental shelf sands south of Delaware toward the Maryland coast was noted by Alexander (1934) in one of the earlier investigations of transects along the continental shelf and it was even suggested that the Delaware River might be the contributing source.

The heavy-mineral suite of the surficial bottom sediments south of Delaware Bay to the vicinity of Cape Fear are more poorly known than the northern shelf areas. Swift, et al. (1971), reporting on analysis of heavy minerals from 20 samples offshore of the Virginia-North Carolina coast, shows that garnet and hornblende remain dominant in the northern direction; no indication of sillimanite content is reflected in this study (see Figure 25). One sample from off Cape Hatteras (Stone and Siegel, 1969) contains relatively low sillimanite and similar highs on garnet and hornblende (see Figure 25). Tyler (1934) in a nearshore study of the heavy minerals along the North Carolina coast between Cape Fear and Cape Hatteras reports higher staurolite than occurs elsewhere along the coast.

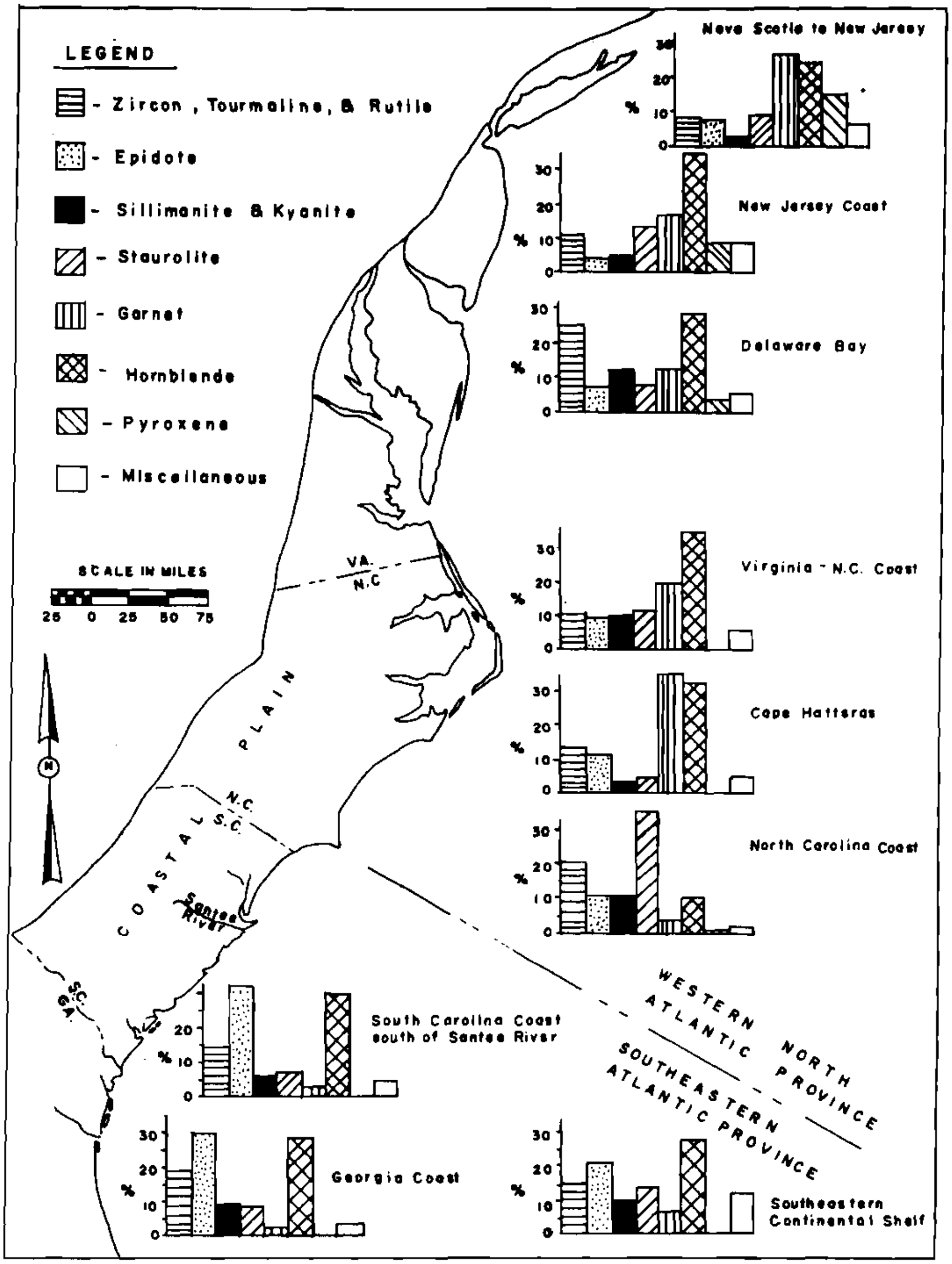


Figure 25. Heavy Mineral Assemblages of the Atlantic Continental Shelf Area. (Investigators from north to south: Ross (1970), McMaster (1954), Swift, et al. (1971), Stone and Siegel (1969), Tyler (1934), Neiheisel and Weaver (1967), and Pilkey (1962))

On the shelf area south of Cape Hatteras, Grosline (1963) mapped the percentage of staurolite in the heavy minerals and found higher values than exist in the mineral provinces in the northern or southeastern shelf areas and mentioned the possibility of a staurolite-rich province for this continental shelf area.

Heavy Minerals of the Southeastern Continental Shelf Area

The heavy minerals of the southeastern Atlantic shelf have been investigated by Pilkey (1963). On the basis of his findings, an epidote-rich province was established from the vicinity of Cape Fear southward to the limits of the Atlantic shelf (see Figures 25 and 26). Investigations of the deltas, coastal areas, and rivers of the South Carolina coast by Hails and Hoyt (1972), Neiheisel and Weaver (1967), Stone and Siegel (1969), and others reveal a major source of epidote and hornblende is from rivers draining the Piedmont with largest concentrations apparent in the vicinity of Santee River and Winyah Bay areas along the South Carolina coast. The high concentration of epidote and hornblende from Santee River southward and lower concentration to the North Carolina boundary (Figure 25) were observed by Neiheisel (1958) in an investigation of beach sands at two mile intervals along the South Carolina coast. Several streams draining the North Carolina and South Carolina Piedmont converge on this section of coast while the coast north of this focal point is free of streams originating in the Piedmont. Thus, sediments from the north of the Santee River area from eroding Coastal Plain formations would dilute the continental shelf Piedmont source sediments with the resulting abundance of stable heavy minerals such as depicted in Figure 25 for the coast north of the Santee River.

The uniform distribution of epidote for several miles seaward in a southerly direction along the continental shelf from the vicinity of the Santee River is evident from investigations by Neiheisel (1966) and Stone and Siegel (1969); the former accomplished extensive heavy mineral analysis of Santee Delta, Charleston Delta, and Port Royal Sound while the latter performed intensive heavy mineral study of an area off the central South Carolina coast. This investigation shows similar epidote population in the offshore sands of the South Georgia coast. The higher epidote content of the Santee River and delta supports the theory advanced by Hoyt and Henry (1971) that these delta sediments are fossil remnants of former capes constructed of fluvial sediments at a time prior to the marine transgression at the end of the Pleistocene. Such a prominent sediment source containing high epidote and hornblende available for erosion and transport southward onto the continental shelf also supports the view by Carver (1971) that sands off the Georgia coast are from the South Carolina coastal area.

Corroborating evidence of sediment dispersal in a southerly direction along the South Carolina coast from eroding fluvial Piedmont source landforms is observed in the dispersal of kaolinite from the Santee delta. As shown in Figure 26, kaolinite comprises the major portion of the sediment where fines are in greatest concentration off the mouth of the Santee River and dispersal of sediment is in a southerly direction. A similar dispersal pattern of kaolinite is evident from offshore Charleston harbor approaches (see Figure 26).

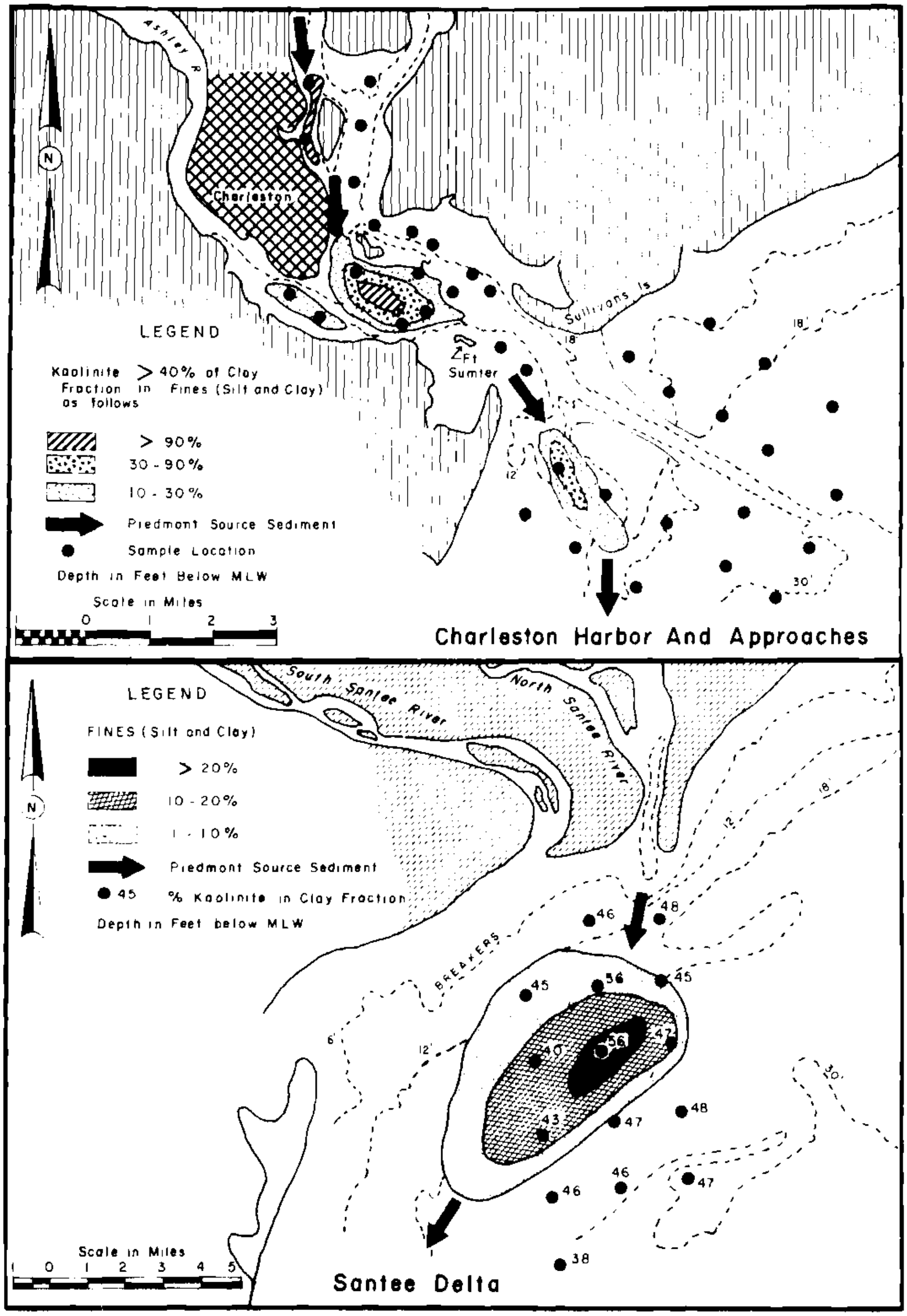


Figure 26. Kaolinite Dispersal Patterns Along the South Carolina Coast as Diagnostic Indicators of Sediment Drift. (After Neiheisel and Weaver (1967))

CHAPTER VIII

SOURCE OF HEAVY MINERALS IN SOUTHEASTERN ATLANTIC COASTAL PLAIN ESTUARIES

Introduction

The heavy minerals of the estuaries of the southeastern Atlantic Coastal Plain were first studied in connection with shoaling problems in the Charleston, Savannah, and Brunswick harbor areas (Neiheisel, 1965). More recently, investigations of estuaries have been extended in scope for more academic interests in both heavy mineral and clay mineral analysis by Neiheisel and Weaver (1967) and Windom, et al. (1971). Some of these estuaries such as the Broad, Brunswick, and Satilla River estuaries have watersheds completely within Coastal Plain formations while the Ogeechee, Savannah, Santee, and Atlamaha River estuaries have watersheds encompassing both Piedmont and Coastal Plain formations. As shown in Figure 27, the texture of the surface sediments within these estuaries varies considerably but all contain some fines; fines are impoverished in all offshore areas except for dispersal paths as depicted in Figure 26. Charleston Harbor estuary is of special interest since it represents an estuary formerly receiving only Coastal Plain sediment discharge but in more recent years under the influence of hydroelectric needs has had man-made diversion of the larger Piedmont source Santee watershed imposed upon it.

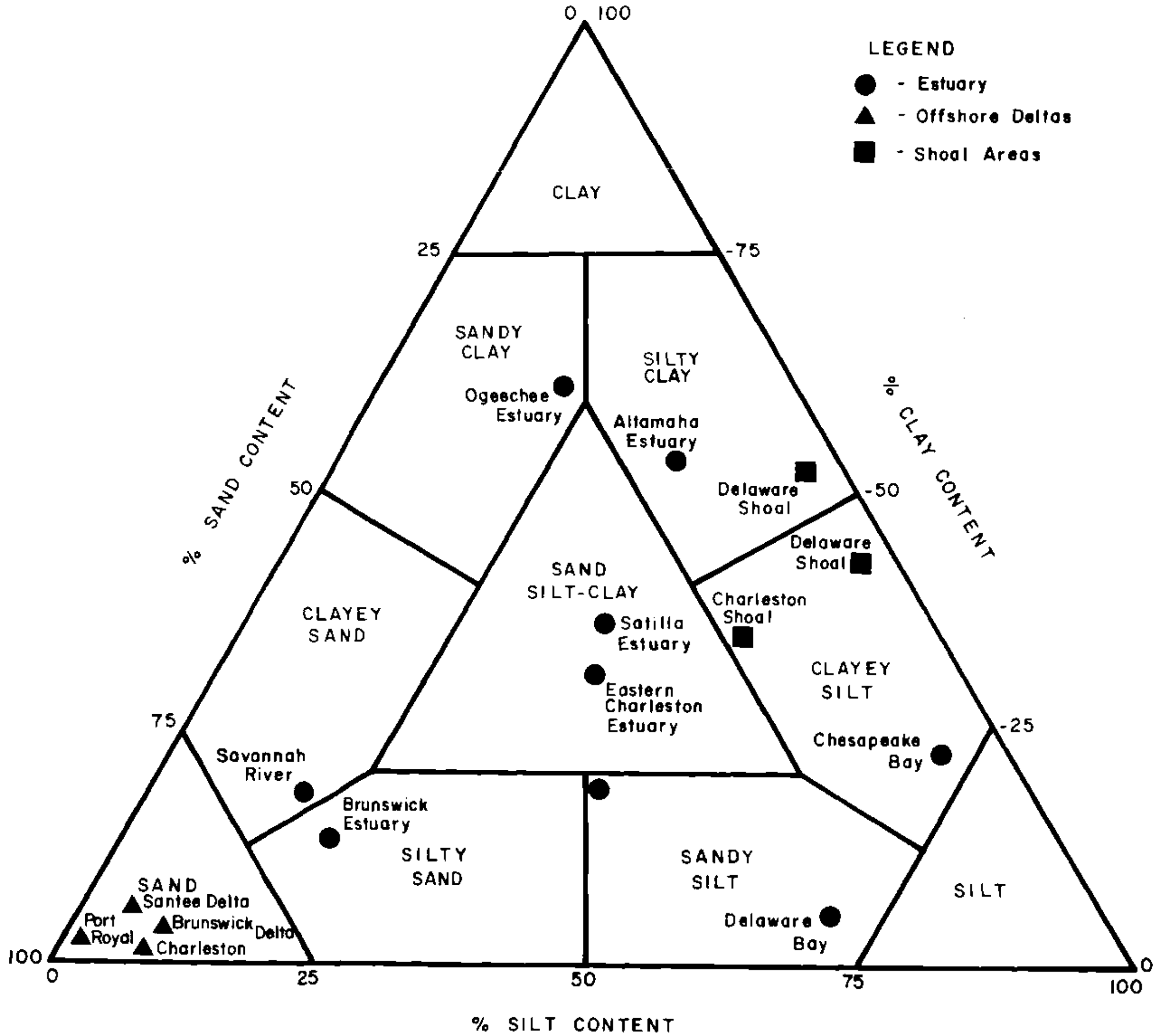


Figure 27. Texture Differences of Surface Sediments of the Northern and Southeastern Atlantic Coastal Plain Estuaries

Southeastern Rivers and Geologic Formations

Several investigators, including Mertie (1953), Dryden and Dryden (1956), Neiheisel (1962 and 1965), Neiheisel and Weaver (1967), Cazeau and Peterson (1970), Windom, Neal, and Beck (1971), Hails and Hoyt (1972), and others have reported on the heavy mineral differences in the Coastal Plain sediments and rivers draining the Coastal Plain. Streams draining the Piedmont crystalline rocks contain an unstable heavy-mineral suite especially high in hornblende and epidote whereas streams draining the Coastal Plain formations are impoverished in unstable mineral species and enriched in stable mineral species such as zircon, tourmaline, and rutile. A comparison of these two extremes may be gained by inspection of the heavy minerals shown for Santee River and the Pamlico Formation shown in Figure 28. Where Coastal Plain streams are tributary to a river originating in the Piedmont Province, the influx of stable mineral species with the unstable heavy mineral assemblage will be generally proportional to the drainage area; thus, it is not surprising that the Santee River with predominant Piedmont drainage area and minor Coastal Plain drainage contains the most unstable heavy mineral assemblage.

That the southeastern Atlantic continental shelf heavy mineral assemblage resembles the heavy mineral assemblage of Piedmont rivers which cross the Coastal Plain sediments was first pointed out by Pilkey (1963). The southeastern shelf heavy minerals are in reality a combination of Piedmont and Coastal Plain heavy minerals with the average heavy mineral assemblage closer to that of the Piedmont. The dilution of Piedmont source heavy minerals as a result of Coastal Plain stream discharge has been demonstrated by Neiheisel and Weaver (1969).

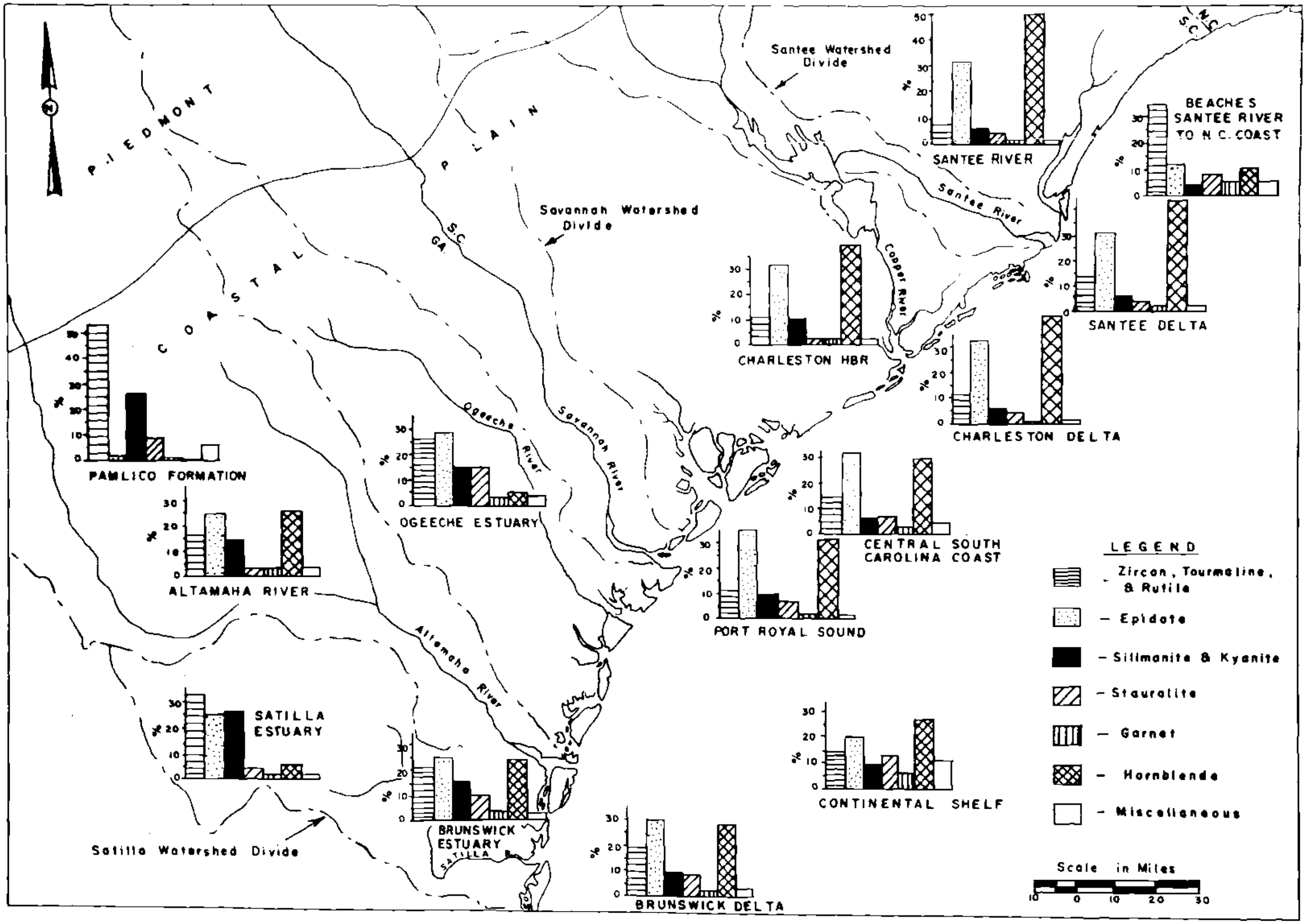


Figure 28. Heavy Mineral Assemblages of Southeastern Estuaries and Adjacent Shelf, Rivers, and Coastal Areas

Charleston Harbor Estuary

Prior to 1942, Charleston Harbor received fluvial discharge from a watershed of low relief in Coastal Plain formations. As a result of the diversion of the waters of the Santee River for the Santee-Cooper hydroelectric project, the watershed area was increased from 1188 square miles to 15,700 square miles and the average discharge of Cooper River increased from 100 cfs to 15,000 cfs. The increased fluvial discharge to a former salt water harbor created a predominance of bottom flood flow creating an effective sediment trap resulting in increased shoaling and pollution in the harbor. Analysis of the shoaling materials (Neiheisel and Weaver, 1967) revealed a composition of more than 90 percent clay with Piedmont source kaolinite several times more abundant than the typical Coastal Plain admixture of montmorillonite, kaolinite, and illite. That the clay minerals are contributed from the Santee watershed to the Cooper River is apparent from the dispersal pattern of the clay minerals; the location of the kaolinite-rich shoals on the west side of the estuary in line with the Cooper River discharge also reflects the source from the diverted watershed. Sand-size material, vastly subordinate to the clay minerals, shows a dispersal pattern of hornblende from a high at the harbor entrance with decreasing amounts up to the Cooper River to a point where it is non-existent (Neiheisel and Weaver, 1967). Other heavy minerals of poor stability show similar distribution patterns. Thus, it is apparent that Lake Moultrie formed by the dam in the upper Cooper River is an effective trap for sand-size sediment but contributes clay minerals in considerable quantity which are flocculated in the harbor sediment trap.

Broad River Estuary

The Broad River estuary is one of the smaller estuaries of the southeastern Atlantic Coastal Plain receiving discharge from the Coosawhatchie River draining low relief Coastal Plain sediments. Dispersal patterns found in diagnostic sepiolite and attapulgite clay minerals and sand-size phosphorite as well as the heavy minerals from the Coosawhatchie River into the Broad River show dilution of these materials rapidly in a seaward direction on the west side of the estuary (Neiheisel and Weaver, 1967). Sediment from the beaches is brought into the estuary on the eastern side in line with the predominant littoral drift from the northern beaches. The heavy mineral distribution of Port Royal also reflects the mixing of typical Coastal Plain sediment with the Piedmont source sediments of the continental shelf. Since the predominant sediment of this estuary is sand-size, it would appear that the sediment source is from the continental shelf into the estuary except for local mixing with Coastal Plain fluvial sediments on the west side of the estuary.

Savannah River Estuary

The Savannah River estuary reflects a typical fluvial Piedmont source heavy-mineral suite but because of the similarity of the heavy mineral assemblage of Piedmont streams receiving considerable dilution from Coastal Plain tributary streams and the mineral assemblage of the southeastern continental shelf sediment, a source determination cannot be readily made on the basis of heavy minerals alone. Clay mineral investigations by (Neiheisel and Weaver, 1967) show a dispersal of kaolinite in the downstream direction in the estuary. Meade (1969) and Neiheisel (1965) have demonstrated that maximum shoaling occurs in estuaries of the southeast during periods of maximum discharge from the watershed; this observation, plus the fact that most of the watershed material is carried on maximum flood conditions, supports the view that the heavy-mineral suite of Savannah Harbor is dominated by a fluvial Piedmont source.

Altamaha River Estuary

The Altamaha River estuary is one of the few major river systems that is not dredged for navigation channels. Meade (1969) has cited navigation channels, because of their tendency to cause predominant bottom flood flow, as one of the major causes of sedimentation in estuaries containing navigation channels. Investigations by Windom, et al. (1971) have established the presence of montmorillonite in suspended samples as being the most significant clay mineral seaward of the estuary; thus, the dispersal pattern of predominantly fluvial Piedmont source kaolinite within the estuary suggests a strong fluvial Piedmont source. Heavy mineral assemblages by Neiheisel (1965) and Windom, et al. (1971) indicate a predominant fluvial Piedmont source of sand-size sediments in the Altamaha River estuary.

Brunswick River Estuary

The heavy mineral assemblage of Brunswick estuary and offshore locations has been cited in an earlier section. The similarity of the heavy mineral assemblages in the estuary and in the continental shelf and the marked difference (i.e., lack of unstable species in the surrounding Coastal Plain formations and upland discharge) are strong evidence that the sand-size sediment is transported from a source on the continental shelf into the estuary. Clay mineral investigation (Neiheisel and Weaver, 1967) of the Brunswick estuary reveals a kaolinite dispersal pattern in the rivers parallel to the coast between the barrier island and mainland which appears to emanate from the Altamaha River and diminish toward the estuary. Thus, while the sand-size sediment is probably transported from the continental shelf by strong tidal currents and littoral currents operating through the tidal inlet between barrier islands, some of the clay may be transported by distributary streams as a fluvial Piedmont source. In this respect, a sediment condition of similar origin exists in Brunswick and Charleston Harbors but the former is by natural agencies whereas the latter is a result of man made causes.

Satilla and Ogeechee Estuaries

Windom, et al. (1971) investigated the Ogeechee River estuary and Satilla River estuary situated on the Georgia coast. The Ogeechee estuary has 90 percent of its drainage area in the Coastal Plain formations while the Satilla River drainage area is completely in Coastal Plain sediments. The Ogeechee River displays a mixed source in its heavy mineral distribution and the contributions of clay minerals also supported the view that fluvial and marine sediments are equally important in this estuary. The heavy-mineral suite and clay mineral suite of the Satilla River suggest to Windom, et al. (1971) that possibly the entire area studied in the estuary is controlled predominantly by transport of offshore material up the estuary.

Santee River Estuary

The Santee River and offshore delta area have been investigated for clay minerals and heavy minerals (Neiheisel and Weaver, 1967) but the estuary portion situated at the interface between the fluvial and marine environment has not been examined to date. However, the greater representation of hornblende and epidote of the sand-size heavy-mineral suite and kaolinite of the clay-mineral suite for both the river and delta in relation to surrounding areas leaves little doubt that the estuary sediments are of fluvial origin with probably negligible contributions from seaward. The dispersal pattern of epidote and kaolinite is especially noted in a southerly direction (see Figure 26).

CHAPTER IX

SUMMARY AND CONCLUSIONS

The estuaries of the Atlantic Coastal Plain have the following possible source areas for sand-size sediments with the following diagnostic heavy minerals:

a. Northern Piedmont source area has a "full" heavy-mineral suite characterized by garnet and hornblende.

b. Southeastern Piedmont source areas have a "full" heavy-mineral suite characterized by epidote and hornblende.

c. Coastal Plain formation, older than Pleistocene, contains a heavy-mineral suite rich in stable zircon, rutile, and tourmaline and impoverished in less stable mineral species.

d. Pleistocene "blanket" deposits of northern Atlantic Coastal Plain and some Piedmont province locations contain a "full" heavy-mineral suite.

e. Continental shelf sands north of Delaware Bay contain a relatively high glacial origin, heavy-mineral suite rich in pyroxene, and impoverished in sillimanite.

f. Continental shelf sands have a predominantly fluvial Piedmont origin with some mixing with fluvial Coastal Plain sediments characterized by heavy-mineral suites rich in hornblende and garnet in the north and hornblende and epidote in the south.

Analysis of more than 140 bottom sediments from tributary streams, Delaware estuary, and continental shelf area in the vicinity of the Delaware Bay capes has delineated four heavy mineral assemblages which reflect upon their origin, correlate with the hydrodynamics of the estuary and the vicinity of the capes, and suggest a transport of sand from the embayed portion of the estuary along former Pleistocene carved surfaces to the continental shelf. The heavy mineral assemblages delineated are depicted in Figure 17 and described below.

1. A fluvial Piedmont source exists in the upper river estuary characterized by a hornblende-garnet heavy-mineral suite; both the hornblende and garnet increase in a seaward direction from Trenton to the bay as a result of contributions from the adjacent Piedmont. The Piedmont source area between Trenton and the bay is relatively free of Pleistocene blanket deposits and contributes a volume of transparent heavy minerals five times as great as the Coastal Plain streams discharging for the same linear distance along the river estuary. The Piedmont streams drain crystalline rocks (schists and gneiss) rich in garnet and hornblende and control points from Trenton to the bay show the steady increase in these minerals toward the bay. Coastal Plain streams impoverished in these minerals are not in control because of their smaller contributions.

2. The upper and central bay areas are characterized by a "full" heavy-mineral suite, i.e., heavy-minerals of all stability ranges and abundant sillimanite. Sillimanite is in similar proportions in this heavy-mineral suite of mixed Coastal Plain and Piedmont source materials and thus maintains a similar value while less resistant Piedmont minerals

(hornblende and garnet) are somewhat reduced in value as are likewise the stable minerals (zircon, rutile, and tourmaline) of the Coastal Plain formations. The "Delaware Bay" heavy mineral province extends the full length of the western bay area. The main source around the bay appears to be Pleistocene formations and local other Coastal Plain formations. A recent investigation of seven bottom samples in the southwest corner of Delaware Bay for heavy minerals by Strom (1972) provides corroborative evidence for including this southwestern bay area in the "Delaware Bay" heavy mineral province. The shelf and coastal area of Delaware are also part of this heavy mineral province.

3. The lower east and central bay areas contain a heavy-mineral suite of mixed "Delaware Bay" and glacially-derived continental shelf sands. Sillimanite in this mixed suite ranges from four to eight percent and pyroxene attains highest values (four percent) of the bay area. This heavy mineral province is the smallest province delineated and is actually a "mixed" province existing between the Delaware Bay province and the glacially derived continental shelf heavy mineral province off the New Jersey coast. This zone is five miles wide with the Delaware submarine channel the southern boundary and the landward boundary nearly 10 miles into the lower bay area.

4. The continental shelf and coastal area off New Jersey contain a heavy-mineral suite relatively impoverished in sillimanite and enriched in pyroxene as compared to the Delaware Bay heavy-mineral province. The sillimanite is generally less than four percent and pyroxenes generally average eight percent; other heavy minerals are similar to the heavy mineral provinces. This heavy-mineral suite is from glacially derived

sediments and eroding coast transported in a southerly direction to the vicinity of Cape May. In the vicinity of Cape May some of the sediment is transported into the bay and some deposited on the shoals fronting the capes.

The hydrodynamic currents and sediment drift are from the shelf into the bay from the New Jersey coast around Cape May and from the shelf into the bay from the Delaware coast around Cape Henlopen. Feldspar distribution along Pleistocene surfaces and heavy mineral provinces provide corroborative evidence of the foregoing and, in addition, indicate that net transport is seaward along the Delaware submarine channel and the western side of the bay to the shelf area and thence south toward the Maryland coast and shelf area.

A significant aspect revealed by the heavy mineral patterns in the vicinity of Delaware Bay is that (a) mixing of sediment does not occur between the capes and (b) sediments along the shelf south of Delaware Bay are similar to those in Delaware Bay whereas shelf sediments to the north of Delaware Bay stand in sharp contrast and reflect a glacial origin.

The southeastern estuaries range from fluvial Piedmont source sediment with but minor dilution of Coastal Plain sediment to those receiving sediment from the shelf area; continental shelf sediment is predominantly a "full" fluvial Piedmont heavy mineral source with some dilution with Coastal Plain sediment containing stable heavy mineral species. Individual estuaries with source areas clearly delineated by the heavy-mineral suite are listed below:

1. The Santee, Savannah, and Altamaha River estuaries situated

at the mouths of major rivers draining both Piedmont and Coastal Plain watershed areas are clearly defined as fluvial Piedmont source with diagnostic hornblende and epidote. Some dilution takes place from tributary Coastal Plain streams with the least amount of dilution in the Santee River as reflected in its highest population of epidote and hornblende.

2. The Satilla, Broad, and Brunswick River estuaries receive upland discharge entirely from streams draining Coastal Plain formations and a dispersal of stable heavy minerals exists to the vicinity of the estuary where a marked change to a "full" heavy-mineral suite rich in epidote and hornblende is evident. The source of the heavy-mineral suite is from the continental shelf through tidal inlets or from distributary streams paralleling the coast with direct discharge from large streams draining the Piedmont and Coastal Formations; the latter is best known from the Brunswick harbor investigation. Thus, while the estuary may exist entirely in Coastal Plain formations, the source is from the streams draining the Piedmont. Eroding land forms of Piedmont fluvial features deposited on a regressing sea during the Pleistocene also provide materials from eroding beaches and coastline for transport around tidal inlets into these small southeastern estuaries.

3. Charleston estuary, situated within a watershed with streams draining Coastal Plain formations and also receiving upland discharge from a dam discharging Piedmont source waters and fine sediment from Santee River is unique in effecting the type of sediment currently being trapped in the harbor estuary. The major portion of sediment being trapped is 95 percent clay with a Piedmont source reflected in the abnormally high

kaolinite content; the pathway of this clay is suspended sediment discharged through the hydroelectric plant at Pinopolis Dam. Sand-size sediment, however, is from the seaward direction with a dispersal of less stable heavy-mineral species in a landward direction. Active sedimentation is thus a large contributing source of fines from the fluvial Piedmont and a rather meager supply of sand (five percent of the total sedimentation) from the high energy continental shelf area via the tidal inlets.

Eventually, with more heavy mineral investigations, a more complete picture of the transition between glacially derived heavy minerals and the predominant Piedmont source sediments will be accomplished and will constitute an important step to delineate the manner of distribution of sand-size sediment on the continental shelf. With more estuarine and coastal studies of heavy minerals, the ability to use heavy minerals as diagnostic indicators of sediment transport by dispersal patterns will become a more realistic indicator of the complex sediment transport problem. The nature of the transgressions and regressions of the sea during Pleistocene time may also be substantially aided by heavy mineral evaluations once enough data have been collected. Perhaps the most complete picture of the hydrodynamics of sediment deposition involved in estuaries and coastline processes will eventually be gained by correlation with investigations of microorganisms, clay minerals, trace elements, and other sediment parameters, in addition to the sand-size heavy minerals.

APPENDIX A

TRANSPARENT HEAVY MINERALS

The percentage of heavy minerals in the 44 to 420 micron size range was determined by subtracting the volume estimate of opaque heavy minerals and mica from the total heavy mineral fraction. The transparent heavy minerals in order of decreasing abundance are: hornblende, garnet, zircon, staurolite, epidote, sillimanite, tourmaline, pyroxene, kyanite, and minor others. Characteristics of the more abundant transparent heavy minerals are listed below.

Amphibole: For convenience in this reconnaissance, all amphiboles have been grouped together. Hornblende greatly predominates with small amounts of actinolite and tremolite often present in addition. The hornblende varies in both color and the intensity of color; most is green and there are lesser amounts of brown and blue-green. The amphiboles retain their characteristic cleavage-controlled prismatic shape but terminations vary from ragged to relatively rounded.

Garnet: The garnets include the colorless, pink, green, and brown varieties. Some well-shaped garnets were found, but the majority of the garnets was well-rounded and smooth. The garnets range from 6 to 38 percent of the Delaware River heavy-mineral suite and locally in the tributaries range up to 49 percent of the transparent fraction. The garnets were easily counted because of the isotropic property under crossed nicols and relatively high index of refraction.

Zircon: Zircon is the most common of the stable heavy minerals. It varies in appearance from nearly clear euhedra to rounded, cloudy, fractured grains. The greatest number group midway between these extremes, being colorless, subangular and subrounded, and usually retaining some evidence of their original prismatic habit. Most appear to be broken rather than worn. An average of one to two percent of the zircon grains is pink; a very few are tan.

Staurolite: Staurolite is especially abundant from locations in some of the Coastal Plain sediments of the upper estuary and is relatively abundant throughout the estuary. It is usually brown in color with a characteristic birefringence color and commonly is pleochroic; inclusions are common in this mineral.

Epidote: Epidote tends to occur in irregular but roughly equidimensional grains or, much more rarely, in crude prisms. Color varies from very pale green, almost colorless, through yellow-greens to rather yellow varieties. High birefrigence is characteristic of this mineral type. Both clinozite and zoisite present in trace amounts to a few percent are included in the epidote group in this investigation.

Sillimanite: The sillimanite examined occurs in colorless, usually prismatic grains. Less common are more or less tabular grains flattened parallel to 001 which could easily be mididentified except that they yield acute bisectrix interference figures showing the distinçtive small 2V of sillimanite. The fibrous variety, fibrolite, is included here and comprises between 10 and 20 percent of the total sillimanite.

Tourmaline: The tourmaline is characteristic of an igneous source and relatively persistent between a few and several percent in all the samples. Pleochroism and elongated shape are the most diagnostic identifying properties of this mineral. Yellow to brown pleochroism is by far the more common but minor blue and pink varieties were also observed.

Kyanite: The kyanite occurs as a colorless to pale blue, elongated to tabular mineral more common in the larger sieve sizes.

Rutile: A red to reddish brown mineral common as an accessory mineral in igneous rock and one of the more stable heavy minerals.

Pyroxenes: Both clinopyroxenes and orthopyroxenes were represented in the river and tributaries with orthopyroxenes, the more abundant. The clinopyroxene were predominantly augite with trace amounts of diopside, and the orthopyroxenes were normally hypersthene with an occasional crystal of enstatite. Hypersthene was distinguished from enstatite by more pleochroism, and from the clinopyroxenes by parallel extinction.

Chloritoid: Bow-tie structured chloritoid comprises up to one percent of the heavy-mineral suite. This mineral is easily recognized because of its characteristic structure.

Other: Minerals of this category occur in amounts ranging from trace amounts to as much as a few percent locally. In general order of decreasing abundance, they include apatite, monazite, wollastonite, sphene, and corundum.

Table 4. Composition of Transparent Heavy-Mineral Fraction in Sediment of Tributary Rivers, Delaware Estuary, Delaware Bay, and the Continental Shelf

Field Location	% Heavy Minerals	% Opaque Fraction	% Transparent Fraction	Hornblende	Actinolite	Tremolite	Clinopyroxene	Hypersthene	Sillimanite	Kyanite	Staurolite	Garnet	Zircon	Rutile	Epidote	Tourmaline	Chloritoid	Other
TRIBUTARY STREAMS																		
Delaware River N. of Trenton																		
S-1	6.0	40	60	27	2	2	2	2	7	1	3	8	26	4	10	2	Tr	4
Brandywine Creek																		
S-4	15.0	33	67	29	3	-	-	3	3	Tr	6	49	1	1	3	Tr	-	2
Mantua Creek																		
S-7	2.9	86	14	11	Tr	-	Tr	2	8	4	20	4	33	6	3	8	-	1
Rancocas Creek																		
S-8	3.6	66	34	8	1	-	-	1	16	4	6	8	28	7	9	9	-	3
Crosswick Creek																		
S-9	2.0	76	24	5	-	-	Tr	2	11	3	37	7	23	3	2	5	-	2
Chester River																		
S-10	14.6	46	54	51	1	-	Tr	2	8	4	4	10	11	3	2	2	-	2
Christina River																		
S-11	5.0	52	48	47	2	Tr	1	2	13	2	6	9	10	2	2	1	Tr	3
Neshaminy Creek																		
S-13	4.1	49	51	32	2	-	1	1	9	3	8	35	3	1	Tr	2	-	3
C $ D Canal																		
S-17	2.0	70	30	10	Tr	-	Tr	3	13	5	33	8	13	4	2	4	1	4
Murderkill River																		
S-18	0.3	85	15	9	3	3	1	2	10	7	10	4	33	3	8	4	-	3
St. Jones River																		
S-19	1.0	75	25	8	Tr	-	1	1	15	7	9	3	39	3	8	3	Tr	3
Leipsic River																		
S-20	4.5	90	10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Mispillion River																		
S-21	1.9	41	59	28	3	-	Tr	2	8	3	4	11	18	2	14	3	-	4
Salem River																		
S-27	1.0	62	38	9	Tr	-	Tr	1	12	4	22	7	31	6	2	2	-	4
Maurice River																		
S-28	2.2	28	72	17	Tr	-	Tr	2	14	2	14	5	33	4	3	3	-	3
Cohansey River																		
S-29	2.0	71	29	2	-	-	-	-	6	3	15	4	59	2	3	3	-	3
Schuylkill River (Average of 13 Samples)																		
S-3	3.0	65	35	37	-	2	4	2	7	5	Tr	9	11	3	11	6	-	3
DELAWARE ESTUARY																		
R232	2.0	10	90	24	1	Tr	1	1	6	2	8	38	8	1	4	3	-	3
R233	3.0	40	60	52	1	-	1	1	3	1	3	17	6	3	5	4	-	3
S34	2.0	20	80	33	1	-	1	2	7	1	6	17	22	2	2	3	-	3
S35	1.4	27	73	39	1	Tr	Tr	1	9	2	10	16	11	2	4	2	-	3
R1	2.0	25	75	32	2	Tr	2	7	9	2	8	16	8	2	5	3	1	3
R14	6.7	33	67	34	3	Tr	1	6	10	2	6	14	10	3	4	4	-	2
R15	2.0	33	67	35	4	1	1	4	11	3	4	10	13	4	4	4	-	3
R22	7.0	25	75	28	3	Tr	1	6	9	2	7	13	15	2	8	4	-	2
R35	2.0	25	75	40	5	Tr	1	3	8	1	3	12	14	2	4	4	-	3
R36	3.0	17	83	34	4	Tr	1	4	8	1	5	13	14	2	6	4	-	4
R48	3.0	15	85	34	2	Tr	1	7	8	1	5	14	12	2	7	3	2	2

Table 4. Continued

Field Location	% Heavy Minerals	% Opaque Fraction	% Transparent Fraction	Hornblende	Actinolite	Tremolite	Clinopyroxene	Hypersthene	Sillimanite	Kyanite	Staurolite	Garnet	Zircon	Rutile	Epidote	Tourmaline	Chloritoid	Other
								DELAWARE ESTUARY										
R52	3.6	75	25	28	2	Tr	1	3	10	2	7	6	33	2	4	1	Tr	2
R65	2.0	15	85	30	2	-	3	5	8	3	6	14	18	3	2	3	Tr	3
R80	1.5	24	76	40	4	-	1	3	7	4	3	10	17	2	4	3	-	2
S30	0.3	18	82	38	4	-	1	3	7	3	3	12	19	2	3	2	-	3
R124	3.0	14	86	36	4	-	1	2	6	4	3	16	19	2	3	1	Tr	3
R139	3.9	13	87	34	3	Tr	2	5	7	3	6	13	17	2	2	3	-	3
R153	3.0	10	90	43	3	-	1	3	8	3	2	13	19	1	1	2	Tr	1
R167	2.8	8	92	37	5	-	1	1	12	5	4	11	14	2	4	2	Tr	2
R181	2.0	69	31	48	3	-	Tr	2	11	3	4	7	14	2	3	2	Tr	1
R188	3.0	13	87	50	3	-	Tr	2	8	3	2	10	15	2	1	2	Tr	2
R200	3.7	9	91	51	3	-	1	2	6	4	2	11	14	1	1	1	Tr	3
R222	7.1	6	94	46	2	-	1	2	6	3	1	14	18	1	2	2	Tr	2
R231	4.5	19	81	43	2	-	2	1	7	3	5	10	17	3	4	2	-	1
								DELAWARE BAY										
B-1	5.0	2	98	55	3	-	-	3	6	1	2	6	9	9	2	1	-	2
B-2	2.5	3	97	59	2	Tr	1	2	5	1	2	10	7	5	2	2	-	2
B-3	2.1	10	90	46	2	1	2	2	5	1	4	11	6	13	2	2	-	3
B-4	6.4	2	98	45	3	2	1	3	6	1	1	20	8	6	1	1	-	2
B-5	1.2	20	60	40	2	2	2	2	6	3	4	13	8	12	2	2	-	2
B-6	3.2	63	37	13	1	Tr	Tr	1	5	1	9	10	5	45	2	5	Tr	3
B-7	6.8	5	95	34	3	2	1	1	4	1	2	34	6	6	Tr	2	Tr	2
B-8	3.5	3	97	44	3	-	2	2	7	2	1	16	7	9	1	2	1	3
B-9	0.5	5	95	53	3	1	1	3	7	Tr	Tr	13	7	6	Tr	2	-	4
B-10	0.8	15	85	26	2	Tr	1	1	7	3	17	24	7	8	Tr	3	-	2
B-11	0.8	44	56	13	2	-	1	1	6	4	23	23	6	15	Tr	5	-	1
B-12	0.3	33	67	31	2	-	2	1	13	5	12	6	7	8	2	7	-	4
B-13	0.9	31	69	40	2	Tr	1	1	5	1	6	22	5	12	1	2	-	2
B-14	1.4	21	79	31	3	Tr	1	2	8	2	8	20	8	10	1	4	-	2
B-15	2.1	13	87	39	3	1	1	3	4	Tr	2	25	6	10	1	3	-	2
B-16	1.8	19	81	40	2	1	1	2	6	2	3	20	6	12	1	3	-	2
B-17	4.8	10	90	44	3	1	1	2	6	1	3	16	9	9	1	2	-	2
B-18	3.9	60	40	19	2	Tr	1	1	6	2	15	16	5	27	1	3	-	2

Table 4. Continued

Field Location	% Heavy Minerals	% Opaque Fraction	% Transparent Fraction	Hornblende	Actinolite	Tremolite	Clinopyroxene	Hypersthene	Sillimanite	Kyanite	Staurolite	Garnet	Zircon	Rutile	Epidote	Tourmaline	Chloritoid	Other
DELAWARE BAY BEACH AT MHW																		
BS-1	3.5	25	75	13	2	-	Tr	1	14	4	33	14	4	2	5	5	-	3
BS-2	3.6	68	32	2	-	-	-	-	6	2	40	17	24	2	2	3	-	2
BS-3	0.5	48	52	2	-	-	-	-	16	3	45	17	4	1	2	8	-	3
BS-4	0.3	30	70	7	2	-	-	1	19	4	21	8	20	3	6	6	-	3
BS-5	0.1	82	18	4	-	-	-	-	36	6	21	4	9	2	6	8	-	4
BS-6	0.2	89	11	3	Tr	2	-	-	17	3	20	4	31	5	3	10	-	2
BS-7	0.3	50	50	11	2	-	-	2	22	3	19	5	18	5	4	7	-	2
BS-8	1.4	84	16	3	Tr	Tr	-	1	13	3	31	9	26	3	2	5	-	4
BS-9	0.3	71	29	6	-	-	-	1	15	5	34	10	12	3	3	9	-	2
BS-10	0.2	50	50	4	1	-	-	2	16	2	18	16	24	1	4	10	-	2
BS-11	0.9	50	50	14	3	-	-	2	8	3	15	23	18	5	4	3	-	2
BS-12	5.6	40	60	30	3	-	-	2	10	2	5	12	12	2	17	3	-	2
BS-13	3.0	30	70	44	3	-	1	3	7	2	3	19	5	1	8	2	Tr	2
BS-14	1.2	50	50	9	1	-	-	2	8	3	18	21	19	8	5	4	-	2
BS-15	5.6	40	60	31	2	Tr	2	Tr	17	2	18	3	8	2	7	5	-	3
BS-16	0.8	-	-	9	2	Tr	Tr	1	5	2	9	10	43	4	8	4	Tr	3
BS-17	1.1	78	22	5	2	1	-	1	5	3	9	9	41	6	14	2	-	2
BS-18	2.5	82	18	7	1	-	-	Tr	15	2	34	8	19	2	7	3	-	2
BS-19	0.6	68	32	16	1	Tr	1	Tr	25	3	18	2	18	2	7	3	-	2
BS-20	0.5	80	20	12	3	-	-	1	20	2	5	4	24	4	20	3	-	2
BS-21	0.6	27	73	28	3	Tr	Tr	2	12	3	10	13	10	2	9	6	Tr	2
CONTINENTAL SHELF																		
C-93 Top	2.0	40	60	55	2	1	-	3	2	1	3	14	9	2	7	2	-	3
C-93 4'	2.4	50	50	40	2	2	1	3	4	1	3	20	9	2	6	5	-	2
C-95 Top	0.8	50	50	15	1	1	1	1	4	4	15	37	12	1	1	5	-	2
C-100 Top	8.1	50	50	31	1	2	1	1	3	1	6	18	23	3	4	3	-	3
C-108 Top	1.5	40	60	21	1	3	2	1	2	6	9	27	12	2	5	5	-	3
C-123 Top	1.6	80	20	26	1	1	1	3	6	3	18	20	10	1	3	4	-	2

Table 4. Concluded

Field Location	% Heavy Minerals	% Opaque Fraction	% Transparent Fraction	Hornblende	Actinolite	Tremolite	Clinopyroxene	Hypersthene	Sillimanite	Kyanite	Staurolite	Garnet	Zircon	Rutile	Epidote	Tourmaline	Chloritoid	Other
CONTINENTAL SHELF																		
C-132 5'	0.3	30	70	22	2	Tr	Tr	2	12	8	28	10	2	1	Tr	12	-	2
C-152 Top	4.4	30	70	23	2	1	Tr	4	4	1	7	21	24	4	4	3	-	2
C-152 1'	1.6	40	60	27	2	Tr	Tr	2	7	2	9	16	17	4	5	4	-	2
C-167 Top	2.0	40	60	19	2	3	1	1	4	3	27	19	6	2	1	10	-	2
C-167 5'	2.0	40	60	26	1	1	1	1	2	2	11	18	21	2	6	5	-	3
C-170 Top	2.8	40	60	41	2	1	1	2	4	2	6	20	11	2	5	2	-	2
C-171 Top	5.2	40	60	33	1	1	1	2	2	1	3	18	25	4	5	2	-	2
C-171 6'	2.0	20	80	11	2	2	1	1	20	3	24	5	14	3	5	7	-	2
C-173 Top	3.9	50	50	48	1	2	1	1	2	2	5	12	9	4	5	5	-	3
C-182 Top	1.7	40	60	30	2	1	1	1	7	3	6	16	15	3	6	2	-	3
C-183 Top	1.2	50	50	28	2	1	1	2	2	2	10	19	15	2	5	4	-	3
C-183 5'	1.7	40	60	27	2	1	1	2	8	2	10	17	14	3	6	5	-	2
REHOBOTH BEACH (Average of 3 samples)																		
C-308, 9, $ 10	0.8	40	60	30	2	3	1	1	13	2	15	11	5	1	8	5	Tr	3

NOTES: 1. Mica ranges between trace amounts and 3% of the transparent heavy mineral fraction; this mineral is not reported with the transparent heavy-mineral suite.

2. Other includes apatite, sphene, andalusite, monazite, wollastonite, topaz, corundum, and minor others.

3. Epidote includes clinozosite and zosite; clinopyroxene includes augite and diopside.

4. Continental Shelf samples have median diameter range between 0.19 and 0.50 mm except for C-167-Top (0.55 mm) and C-171-6' (0.80 mm).

Table 5. Composition of Transparent Heavy Mineral Fraction in Beach Profile and Offshore Samples of Delaware Bay

Field No.	Location	Hornblende	Actinolite	Tremolite	Clinopyroxene	Hypersthene	Sillimanite	Kyanite	Staurolite	Garnet	Zircon	Rutile	Epidote	Tourmaline	Other
						Sea Breeze Beach, N. J.									
1	Dune	4	2	--	Tr	Tr	15	2	20	4	30	5	6	9	3
2	Beach, M.H.W.	5	1	Tr	1	1	20	4	22	2	30	2	3	6	3
3	Beach, M.W.	8	1	--	1	Tr	6	2	17	2	48	5	2	5	3
4	Beach, M.L.W.	16	1	Tr	Tr	Tr	10	4	17	1	32	6	2	8	3
5	Offshore, 3 ft.	7	1	1	1	1	18	3	13	2	33	6	5	6	3
6	Offshore, 6 ft.	10	1	--	Tr	1	14	4	20	3	31	6	3	5	2
7	Offshore, 9 ft.	11	2	Tr	Tr	1	15	2	18	7	32	2	2	5	3
8	Offshore, 12 ft.	19	2	Tr	Tr	1	20	2	12	10	20	4	5	3	2
						Thompson Beach, N. J.									
1	Dune	12	2	Tr	--	Tr	13	3	17	12	20	4	7	7	3
2	Beach, M.H.W.	16	1	1	2	1	20	7	20	4	7	2	3	13	3
3	Beach, M.W.	9	1	1	2	1	19	5	28	9	10	4	3	4	4
4	Beach, M.L.W.	14	1	1	Tr	1	15	3	30	8	13	1	4	7	2
5	Offshore, 3 ft.	9	1	Tr	1	1	16	4	32	9	13	1	3	7	3

Table 5. Continued

Field No.	Location	Hornblende	Actinolite	Tremolite	Clinopyroxene	Hypersthene	Sillimanite	Kyanite	Staurolite	Garnet	Zircon	Rutile	Epidote	Tourmaline	Other
6	Offshore, 6 ft.	9	2	1	Tr	1	15	2	23	11	24	4	2	4	2
7	Offshore, 9 ft.	14	1	Tr	1	1	15	3	20	8	24	2	4	5	2
8	Offshore, 12 ft.	8	1	Tr	--	2	15	3	26	14	16	2	7	4	2
	Miami Beach, Villas, N. J.														
1	Dune	1	1	Tr	1	1	19	7	19	3	23	9	3	10	3
2	Beach, M.H.W.	11	1	1	1	1	22	3	19	2	24	3	4	5	3
3	Beach, M.W.	2	Tr	Tr	1	1	21	3	13	10	30	5	5	6	3
4	Beach, M.L.W.	2	1	Tr	1	1	14	2	26	3	34	2	2	9	3
5	Offshore, 3 ft.	6	1	Tr	1	1	8	2	25	7	35	4	4	3	3
6	Offshore, 6 ft.	5	2	Tr	1	1	13	2	7	1	48	5	8	4	3
7	Offshore, 9 ft.	32	3	1	1	1	12	1	6	14	13	2	8	3	3
8	Offshore, 12 ft.	32	1	Tr	1	2	6	1	3	20	16	5	9	2	2
	Woodland Beach, Del.														
1	Dune	16	1	1	Tr	1	34	4	19	9	5	Tr	1	6	3
2	Beach, M.H.W.	7	1	1	1	1	7	3	28	13	25	3	4	3	3

Table 5. Continued

Field No.	Location	Hornblende	Actinolite	Tremolite	Clinopyroxene	Hypersthene	Sillimanite	Kyanite	Staurolite	Garnet	Zircon	Rutile	Epidote	Tourmaline	Other
3	Beach, M.W.	18	2	1	--	1	25	3	18	6	18	2	2	2	2
4	Beach, M.L.W.	17	2	1	1	1	16	2	16	9	20	2	7	4	2
5	Offshore, 3 ft.	8	1	1	1	1	13	1	6	4	50	4	5	3	2
6	Offshore, 6 ft.	25	3	1	1	1	20	2	8	4	21	1	6	4	3
7	Offshore, 9 ft.	38	2	Tr	1	Tr	6	Tr	6	11	24	1	7	2	2
8	Offshore, 12 ft.	32	2	Tr	1	Tr	5	Tr	2	23	24	3	5	1	2
							Pickering Beach, Del.								
1	Dune	35	2	2	1	1	34	5	3	2	2	2	5	3	3
2	Beach, M.H.W.	27	3	1	Tr	1	30	4	14	2	4	Tr	8	4	2
3	Beach, M.W.	15	4	2	1	1	20	1	8	3	22	3	13	4	3
4	Beach, M.L.W.	51	2	1	Tr	Tr	4	Tr	1	11	19	1	8	Tr	2
5	Offshore, 3 ft.	27	2	Tr	1	1	18	3	7	4	22	1	11	1	2
6	Offshore, 6 ft.	33	2	2	Tr	1	8	1	5	10	22	3	6	4	3
7	Offshore, 9 ft.	38	2	3	1	2	7	1	Tr	16	20	2	4	1	3
8	Offshore, 12 ft.	44	2	Tr	1	1	7	1	1	17	14	1	8	1	2

Table 5. Continued

Field No.	Location	Horn-blende	Ac-tino-lite	Tremo-lite	Clino-pyrox-ene	Hyper sthene	Sill-iman-ite	Ky-an-ite	Staur-olite	Gar-net	Zir-con	Ru-tile	Epi-dote	Tour-ma-line	Other
	Bowers Beach, Del.														
1	Dune	12	2	1	1	1	25	5	25	9	4	Tr	5	7	3
2	Beach, M.H.W.	13	2	2	1	1	21	3	13	4	18	1	14	4	3
3	Beach, M.W.	23	3	2	1	1	6	2	6	4	27	4	15	3	3
4	Beach, M.L.W.	16	2	1	1	1	14	3	5	4	29	2	14	5	3
5	Offshore, 3 Ft.	14	1	2	1	2	12	1	21	8	20	3	8	4	3
6	Offshore, 6 Ft.	43	1	Tr	--	Tr	5	1	4	7	25	4	5	2	3
7	Offshore, 9 Ft.	40	1	1	1	1	6	Tr	1	15	19	2	9	2	2
8	Offshore, 12 Ft.	38	2	2	1	2	3	Tr	1	14	24	2	6	2	3
	Broadkill Beach, Del.														
1	Dune	20	2	1	Tr	1	26	5	5	13	7	1	11	5	3
2	Beach, M.H.W.	13	3	5	1	1	26	4	11	2	9	2	10	10	3
3	Beach, M.W.	20	2	1	Tr	1	15	4	10	9	20	1	10	5	2
4	Beach, M.L.W.	6	1	1	Tr	1	9	1	11	7	46	5	8	2	2
5	Offshore, 3 Ft.	14	2	Tr	Tr	2	34	2	11	3	6	2	14	7	3

Table 5. Concluded

Field No.	Location	Horn-blende	Ac-tino-lite	Tremo-lite	Clino-pyrox-ene	Hyper sthene	Sill-iman-ite	Ky-an-ite	Staur-olite	Gar-net	Zir-con	Ru-tile	Epi dote	Tour-ma-line	Other
6	Offshore, 6 Ft.	9	1	2	Tr	Tr	10	1	11	10	36	4	9	4	3
7	Offshore, 9 Ft.	32	3	3	Tr	1	8	1	2	10	20	1	11	5	3
8	Offshore, 12 Ft.	15	1	1	Tr	Tr	16	2	14	6	28	1	11	2	3

NOTES:

1. Others, in order of decreasing abundance include andalusite, chloritoid, sphene, apatite, monazite, wollastonite, topaz, and rare miscellaneous types.
2. Mica (muscovite, biotite, and phlogophite) is not included in transparent heavy-mineral fraction.
3. Epidote fraction includes epidote and minor occurrences of zoisite and clinozosite.
4. Sillimanite includes the variety fibrolite.
5. A statistical point-count was performed on each sieve-size constituting more than 10% of the heavy minerals; each heavy-mineral sieve-size fraction was weighted for the point-count of each mineral and the average composition determined.

BIBLIOGRAPHY

Alexander, A. E., 1934, A petrographic and petrologic study of some continental shelf sediments: Jour. Sed. Petrology, v. 4, n. 1, p. 12-22.

Biggs, R. B., 1967, The sediments of Chesapeake Bay, in Lauff, G. H., ed., Estuaries: Am. Assoc. for Adv. of Science, Pub. No. 83, p. 239-260.

Bumpus, D. F., 1965, Residual drift along the bottom on the continental shelf in the Middle Atlantic shelf area: Limol. and Oceanog., Supplement to vol. 3, p. 48-53.

Carver, R. E., 1971, Holocene and Late Pleistocene sediment sources, continental shelf off Brunswick, Georgia: Jour. Sed. Petrology, v. 41, p. 517-525.

Cazeau, C. J., 1962, Value of heavy mineral investigation in the Coastal Plain of South Carolina: Geologic Notes, South Carolina Dev. Brd. Div. of Geology, v. 6, n. 4, p. 43-44.

Cazeau, C. J. and Peterson, R. W., 1970, Lynches River sediments, S. C.: Geologic Notes, S. C. Dev. Brd. Div. of Geology, v. 14, n. 4, p. 85-86.

Clifton, H. E., Hunter, R. E., and Phillips, R. L., 1971, Depositional structures and processes in the nonbarred high-energy nearshore: Jour. Sed. Petrology, v. 41, p. 651-670.

Doeglas, D. J., 1940, The importance of heavy mineral analysis for regional sedimentary petrology: Rept. Comm. Sedimentation, 1939-40, Nat. Res. Council, 108 pp.

Dryden, L., 1958, Monazite in part of the southern Atlantic Coastal Plain: U. S. Geol. Survey Bull. 1042-L, p. 393-429.

Dryden, L. and Dryden, C., 1946, Comparative rates of weathering of some common heavy minerals: Jour. Sed. Petrology, v. 16, p. 91-96.

Emery, K. O., 1966, Atlantic continental shelf and slope of the United States: Geological Survey Prof. Paper 529-A, p. 23.

BIBLIOGRAPHY (Continued)

Fairchild, J. C., 1966, Correlation of littoral transport with wave energy along the shores of New York and New Jersey: U. S. Army, Corps of Engineers Coastal Eng. Research Center Tech. Mem. 18, 35 pp.

Fields, E. F., and Pilkey, O. H., 1969, Feldspar in Atlantic continental margin sands off the southeastern United States: Bull. Geol. Soc. Amer., v. 80, p. 2097-2102.

Folk, R. L., 1968, Petrology of sedimentary rocks: Univ. of Texas, Hemphills Book Store, Austin, Texas, 170 pp.

Giles, R. T., and Pilkey, O. H., 1965, Atlantic-beach and dune sediments of the southern United States: Jour. Sed. Petrology, v. 35, p. 900-910.

Gorsline, D. S., 1963, Bottom sediments of the Atlantic shelf and slope off the southern United States: Jour. Geology, v. 71, p. 422-440.

Groot, J. J., 1955, Sedimentary petrology of the Cretaceous sediments of northern Delaware in relation to paleogeographic problems: Del. Geol. Survey Bull. No. 5, 157 pp.

Groot, J. J., and Glass, H. D., 1960, Some aspects of the mineralogy of the northern Atlantic Coastal Plain, in Swineford, Ada, ed., Clay and clay minerals, Nat'l. clays and clay minerals, 7th, Wash., D. C., Oct. 1958 Proc.: Pergamon Press, New York, p. 271-284.

Hails, J. R., and Hoyt, J. H., 1972, The nature and occurrence of heavy minerals in Pleistocene and Holocene sediments of the lower Georgia Coastal Plain: Jour. of Sed. Pet., v. 2, n. 3, p. 646-666.

Hathaway, J. C., 1972, Regional clay mineral facies in the estuaries and continental margin of the United States east coast, in Nelson, B. W., ed., Environmental framework of Coastal Plain estuaries: Geol. Soc. America Tech. Memoir 133 (in press).

Hoyt, J. H., and Henry, V. J., Jr., 1971, Origin of capes and shoals along the southeastern coast of the United States: Geol. Soc. America Bull., v. 82, n. 1, p. 59-66.

Hubert, J. F., and Neal, W. F., 1967, Mineral composition and dispersal patterns of deep-sea sands in the western North Atlantic petrologic province: Bull. Geol. Soc. of Am., v. 78, p. 749-772.

Ippen, A. T., 1966, Sedimentation in estuaries, in Ippen, A. T., ed., Estuary and coastline hydrodynamics: McGraw-Hill, New York, p. 648-672.

BIBLIOGRAPHY (Continued)

Jordan, R. R., 1964, Columbia (Pleistocene) sediments of Delaware: Delaware Geol. Survey Bull., 12, 59 pp.

Jordan, R. R., 1968, Suspended and bottom sediments in the Delaware estuary: Abstract, Geol. Soc. America, North eastern section, p. 37-38.

Jordan, R. R., and Groot, J. J., 1962, Some observations on the sediments of the Delaware River south of Wilmington, Delaware Geological Survey, Invest. No. 6, 12 pp.

Kraft, J. C., 1971a, Sediment facies patterns and geologic history of a Holocene marine transgression: Geol. Soc. American Bull., p. 2121-2158.

Kraft, J. C., 1971b, A guide to the geology of Delaware's coastal environments: Publ. 2GL039 of the College of Marine Studies at the University of Delaware, 220 pp.

Krumbein, W. C., and Pettijohn, F. J., 1938, Manual of sedimentary petrography, Appleton-Century-Crofts, Inc., New York, 549 pp.

Martens, J. H. C., 1935, Beach sands between Charleston, South Carolina and Miami, Florida: Geol. Soc. America Bull., v. 46, p. 1563-1596.

McCarthy, G. R., 1931, Coastal sands of the eastern United States: Amer. J. of Science, v. 22, p. 35-50.

McCauley, C. K., 1960, Exploration for heavy minerals on Hilton Head, South Carolina: South Carolina State Devel. Board, Div. Geology Bull., 26, 11 pp.

McMaster, R. L., 1954, Petrography and genesis of the New Jersey beach sands: New Jersey Dept. Conserv. and Econ. Devel., Geol. Ser., Bull., 63, 239 pp.

McMaster, R. L., and Garrison, L. E., 1966, Mineralogy and origin of southern New England shelf sediments: Jour. Sed. Petrology, v. 36, n. 4, p. 1131-1142.

Meade, R. H., 1969, Landward transport of bottom sediments in estuaries of the Atlantic Coastal Plain: Jour. Sed. Petrology, v. 39, p. 222-234.

Mertie, J. B., 1953, Monazite deposits of the southeastern Atlantic States: U. S. Geol. Survey Circ. 273, p. 1-31.

BIBLIOGRAPHY (Continued)

Milliman, J. D., 1972, Atlantic continental shelf and slope of the United States, petrology of the sand fraction--northern New Jersey to southern Florida: U. S. Geol. Survey Prof. Paper 529-J.

Milliman, J. D., Pilkey, O. H., and Ross, D. A., 1972, Sediments of the continental margin off the eastern United States: Geol. Soc. American Bull., v. 83, p. 1315-1334.

Moody, D. W., 1964, Coastal morphology and processes in relation to the development of submarine sand ridges off Bethany Beach, Delaware: [Ph.D. thesis], Baltimore, Johns Hopkins Univ., 165 pp.

Moxley, F. M., 1970, An Analysis of heavy minerals in sediments of Delaware Bay: [M.S. thesis], Millersville, Millersville State College, 74 pp.

Neiheisel, James, 1958, Origin and heavy minerals of the Isle of Palms, South Carolina: [M.S. thesis], Columbia, University of South Carolina, 32 pp.

Neiheisel, James, 1959, Littoral drift in vicinity of Charleston Harbor: J. of the Waterways and Harbors Division, Proceedings of the American Society of Civil Engineers, v. 85, No. WW2, p. 99-113.

Neiheisel, James, 1962, Heavy mineral investigation of recent and Pleistocene sands of lower Coastal Plain of Georgia, Geol. Soc. America Bull., v. 73, p. 365-374.

Neiheisel, James, 1965, Source and distribution of sediments at Brunswick Harbor and vicinity Georgia: U. S. Army Corps of Engineers Coastal Eng. Research Center Tech., Memo 12, 49 pp.

Neiheisel, James, 1966, Significance of clay minerals in shoaling problems: U. S. Army Corps of Engineers Comm. Tidal Hydraulics Tech. Bull., 10, 30 pp. plus 6 tables.

Neiheisel, James, 1972, Techniques for use of organic and amorphous materials in source investigations of estuarine sediments, in Nelson, B. W., ed., Environmental framework of Coastal Plain estuaries: Geol. Soc. Amer. Memoir 133, p. 359-382.

Neiheisel, James, and Weaver, C. E., 1967, Transport and deposition of clay minerals, southeastern United States: Jour. of Sed. Petrology, v. 37, n. 4, p. 1084-1116.

Oostdam, B. L., 1971, Suspended sediment transport in Delaware Bay: [Ph.D. thesis], Newark, University of Delaware, 316 pp.

BIBLIOGRAPHY (Continued)

Oostdam, B. L. and Jordan, R. R., 1969, Aspects of sediment transport in the Delaware estuary: Abstract Geol. Soc. of America, Southeastern Section, p. 40.

Owens, J. P., and Sohl, N. P., 1969, Shelf and deltaic paleo environments in Cretaceous-Tertiary formations of the New Jersey Coastal Plain, in Subitzky, S., ed., Geology of selected areas in New Jersey and eastern Pennsylvania and guidebook of excursions: Rutgers University Press, New Brunswick, New Jersey, p. 235-278.

Peterson, R. W. and Cazeau, C. J., 1970, Lynches River sediments, South Carolina, Geologic Notes, S. C. State Dev. Board, v. XIV, n. 4, p. 85-96.

Pilkey, O. H., 1963, Heavy minerals of the U. S. South Atlantic continental shelf and slope: Geol. Soc. America Bull., v. 74, p. 641-648.

Pilkey, O. H. and Frankenberg, D., 1964, The relict-recent sediment boundary on the Georgia continental shelf: Georgia Acad. Sci., v. 22, p. 37-40.

Ross, D. A., 1970, Atlantic continental shelf and slope of the United States--heavy minerals of the continental margin from southern Nova Scotia to northern New Jersey: U. S. Geol. Survey Prof. Paper 529-G, 40 pp.

Schubel, J. R., 1968, Suspended sediment of the northern Chesapeake Bay, Chesapeake Bay Institute, Technical Report 35, p. 166.

Shepard, F. P., 1936, Continental shelf sediment off the Mid-Atlantic states: Geol. Soc. America, v. 47, p. 441-458.

Shepard, F. P. and Cohee, G. V., 1936, Continental shelf sediment off the Mid-Atlantic States: Geol. Soc. America Bull., v. 47, p. 441-458.

Smith, J. W., Pickering, S. M., and Landrum, J. R., 1967, Heavy mineral bearing sand of the coastal region of Georgia: Project Report No. 8, South Georgia Mineral Program, Georgia Dept. of Mines and Mining, 68 pp.

Stanley, D. J., Swift, J. P., Silverberg, Norman, Noel, J. P., and Sutton, R. G., 1972, Late quarternary progradation and sand spillover on the outer continental margin off Nova Scotia, southeastern Canada: Smithsonian Contributions to the Earth Sciences, No. 8, Smithsonian Institute Press, Wash., D. C., 88 pp.

Stone, I. C., Jr., and Siegel, F. R., 1969, Distribution and provenance of minerals from continental shelf sediments off the South Carolina coast: Jour. of Sed. Petrology, v. 39, p. 276-296.

BIBLIOGRAPHY (Continued)

Strom, R. N., 1972, Sediment distribution in southwestern Delaware Bay: University of Delaware, College of Marine Studies, Technical Report No. 18, 118 pp.

Swift, Donald J. P., Stanley, D. J., and Curray, J. R., 1971, Relict sediments on continental shelves, a reconsideration: Jour. of Geol., v. 79, p. 322-346.

Swift, Donald J. P., Charles, D. E., Jr., and Mchone, John, 1971, Hydraulic fractionation of heavy mineral suites on an unconsolidated retreating coast: Jour. of Sed. Petrology, v. 41, n. 3, p. 683-690.

Taney, N. E., 1961, Geomorphology of the south shore of Long Island, New York: U. S. Army Corps of Engineers Beach Erosion Board Tech. Man., 128, 50 pp. plus 2 app.

Thom, B. G., Adams, R. D., Cazeau, C. J., and Heron, S. D., Jr., 1972, Aspects of the texture and mineralogy of surficial sediments, Horry and Marion Counties, South Carolina: Southeastern Geology, v. 8, p. 39-58.

Tyler, S. A., 1934, A study of sediments from the North Carolina and Florida coasts: Jour. Sed. Petrology, v. 4, p. 3-11.

U. S. Army Corps of Engineers, 1946, Schuylkill River, Pa.: House Doc. 529, 79th Congress, 2nd Session, Philadelphia, Pa., 43 pp.

U. S. Army Corps of Engineers, 1946, Cold Spring Inlet (Cape May Harbor), N. J.: House Doc. 206, 83d Congress, 1st Session, 53 pp.

U. S. Army Corps of Engineers, 1959, Shore of New Jersey-Barnegat Inlet to Cape May canal, beach erosion control study: House Doc. 208, 86th Congress, 1st Session, Philadelphia, Pa., 107 pp.

U. S. Army Corps of Engineers, 1963, Hurricane study: Atlantic coast of southern New Jersey and Delaware: Report to 84th and 85th Congresses, Philadelphia, Pa., 51 pp.

U. S. Army Corps of Engineers, 1968, Delaware coast, beach erosion control and hurricane protection: Senate Doc. 90, 90th Congress, 2nd Session, Philadelphia, Pa., 110 pp.

U. S. Army Corps of Engineers, 1969, Composition of Delaware estuary bottom sediments: Preliminary report, 10 pp. (unpublished).

BIBLIOGRAPHY (Concluded)

U. S. Army Corps of Engineers, 1970, Source and transportation of shoaling materials in Delaware estuary: Philadelphia, Pa., 42 pp. (unpublished).

U. S. Army Corps of Engineers, 1972, Study of the New Jersey control inlets and beaches; Interim report on Herefort Inlet to the Delaware Bay entrance of the Cape May Canal: Philadelphia, Pa., 78 pp. (unpublished).

U. S. Coast and Geodetic Survey, 1960, Tidal current atlas for Delaware Bay, U. S. Dept. of Commerce, Wash., D. C., 12 pp.

U. S. Department of the Interior, 1970, Water quality of the Delaware River estuary, July through Dec. 1967: Open file Report, 84 pp.

Windom, H. L., Neal, W. J., and Beck, K. C., 1971, Mineralogy of sediments in three Georgia estuaries: Jour. Sed. Petrology, v. 41, n. 2, p. 497-504.

VITA

James Neiheisel was born on June 3, 1927 in Cincinnati, Ohio. He received his undergraduate degree from Ohio State University in 1950. Neiheisel received a regular commission in the U. S. Navy upon graduation and served aboard a destroyer and attack transport as A.S.W. officer and navigation officer; during this period he submitted carefully annotated fathograms to the Oceanographic Office and his destroyer was listed as an outstanding contributor of oceanographic data in 1952. Neiheisel received a Master of Science degree from the University of South Carolina in January 1958. He has since been employed as Chief, Petrographic and Geology Section of the U. S. Army Corps of Engineers South Atlantic Division Laboratory. In January 1963 he was granted a Secretary of Army Research and Fellowship Award to study sediments off the Georgia coast. During this period Neiheisel attended the Georgia Institute of Technology. He has been engaged in studies involving nuclear waste disposal at Savannah River AEC Plant, Interoceanic Canal Studies, and several estuary investigations including Charleston and Delaware estuaries. He has published several papers in national engineering and scientific journals.